CSCE 465 Computer & Network Security

Instructor: Abner Mendoza

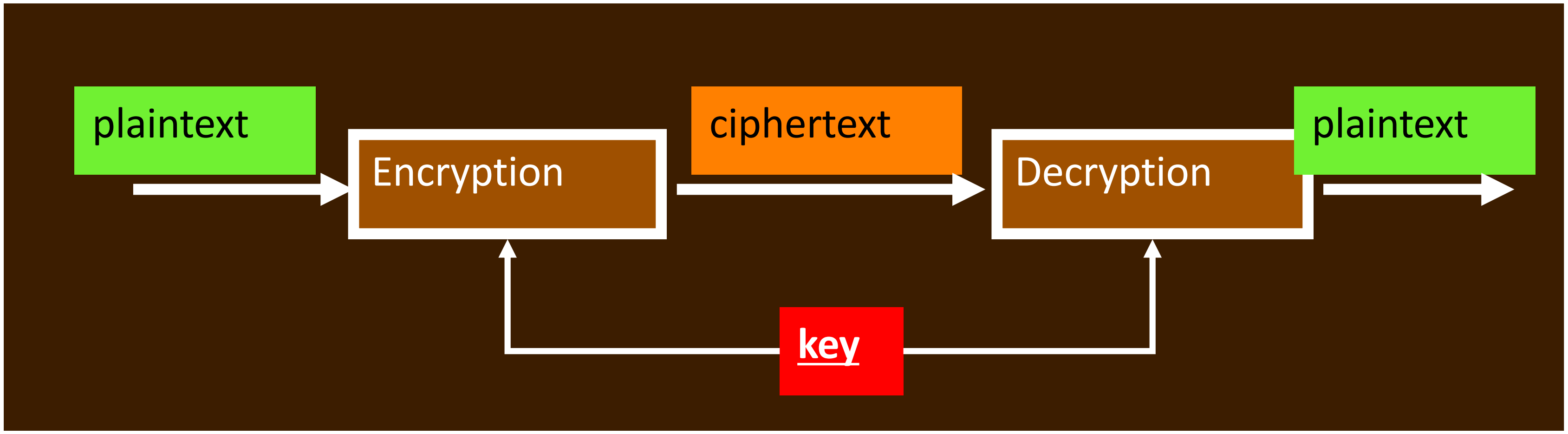
Secret Key Cryptography
(I)

Roadmap

- Overview
- Feistel Cipher
- DES
- AES

Introduction

Secret Key Cryptography



- Same key is used for both encryption and decryption
  - this one key is shared by two parties who wish to communicate securly
- Also known as *symmetric key* cryptography, or *shared key* cryptography

Applications of Secret Key Crypto

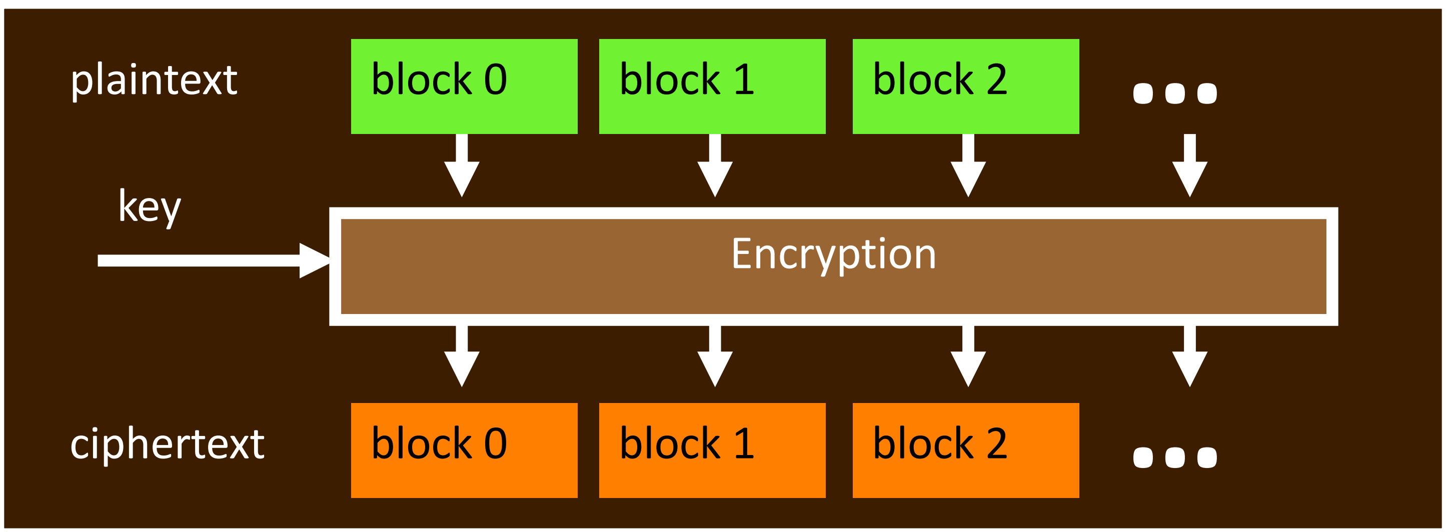
- Communicating securely over an insecure channel
  - Alice encrypts using shared key
  - Bob decrypts result using same shared key
- Secure storage on insecure media
  - Bob encrypts data before storage
  - Bob decrypts data on retrieval using the same key

Applications… (Cont'd)

- *Message integrity*
  - Alice computes a *message integrity code* (MIC) from the message, then encrypts with shared key
  - Bob decrypts the MIC on receipt, and verifies that it agrees with message contents
- *Authentication*
  - Bob can verify Alice sent the message
  - how is that possible?

Generic Block Encryption

- Converts one input plaintext block of fixed size *k* bits to an output ciphertext block also of *k* bits
- Benefits of large *k*? of short *k*?



Key Sizes

- Keys should be selected from a large potential set, to prevent brute force attacks
- Secret key sizes
  - 40 bits were considered adequate in 70’s
  - 56 bits used by DES were adequate in the 80’s
  - 128 bits are adequate for now
- If computers increase in power by 40% per year, need roughly 5 more key bits per decade to stay “sufficiently” hard to break

Notation

Notation	Meaning
$X \oplus Y$	Bit-wise exclusive-or of X and Y
$X \mid Y$	Concatenation of X and Y
$K\{m\}$	Message *m* encrypted with secret key K

Two Principles for Cipher Design

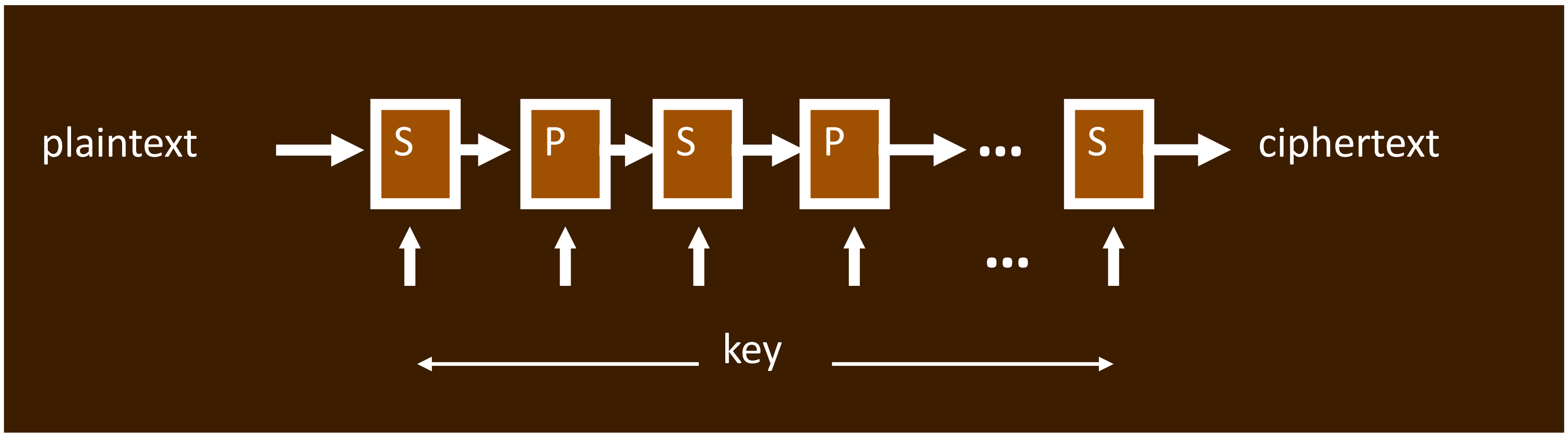
- Confusion:
  - Make the relationship between the <plaintext, key> input and the <ciphertext> output as complex (non-linear) as possible
- Diffusion:
  - Spread the influence of each input bit across many output bits

Exploiting the Principles

- Idea: use multiple, alternating permutations (P) and substitutions (S), e.g.,
  - S→P→S→P→S→…
  - P→S→P→S→P→…
- Do they have to alternate? e.g.…
  - S→S→S→P→P→P→S→S→…??
- Confusion is mainly accomplished by substitutions
- Diffusion is mainly accomplished by permutations
- Example ciphers: DES, AES

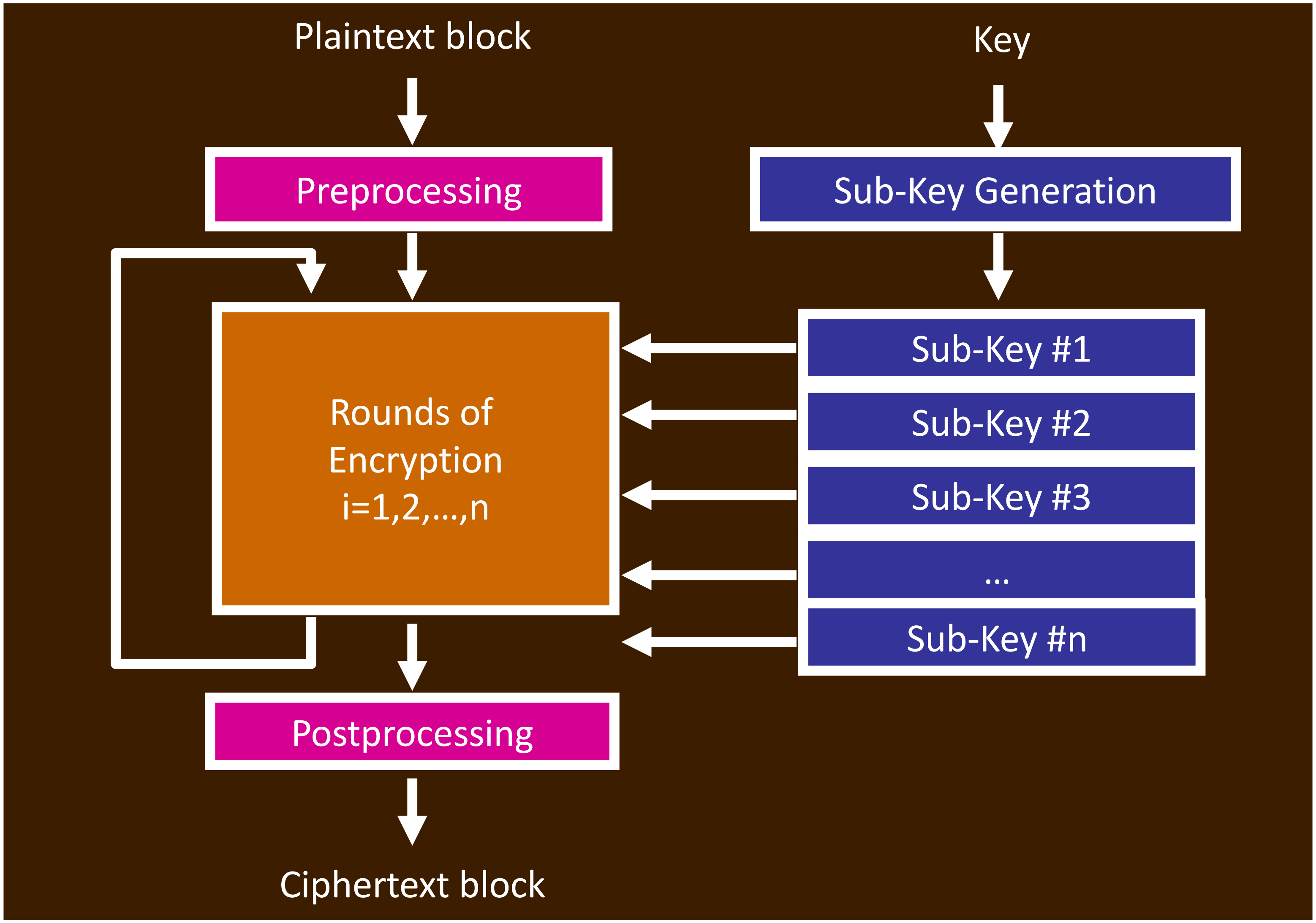
Secret Key… (Cont'd)

- Basic technique used in secret key ciphers: multiple applications of alternating substitutions and permutations



Well-known examples: DES, AES

Basic Form of Modern Block Ciphers



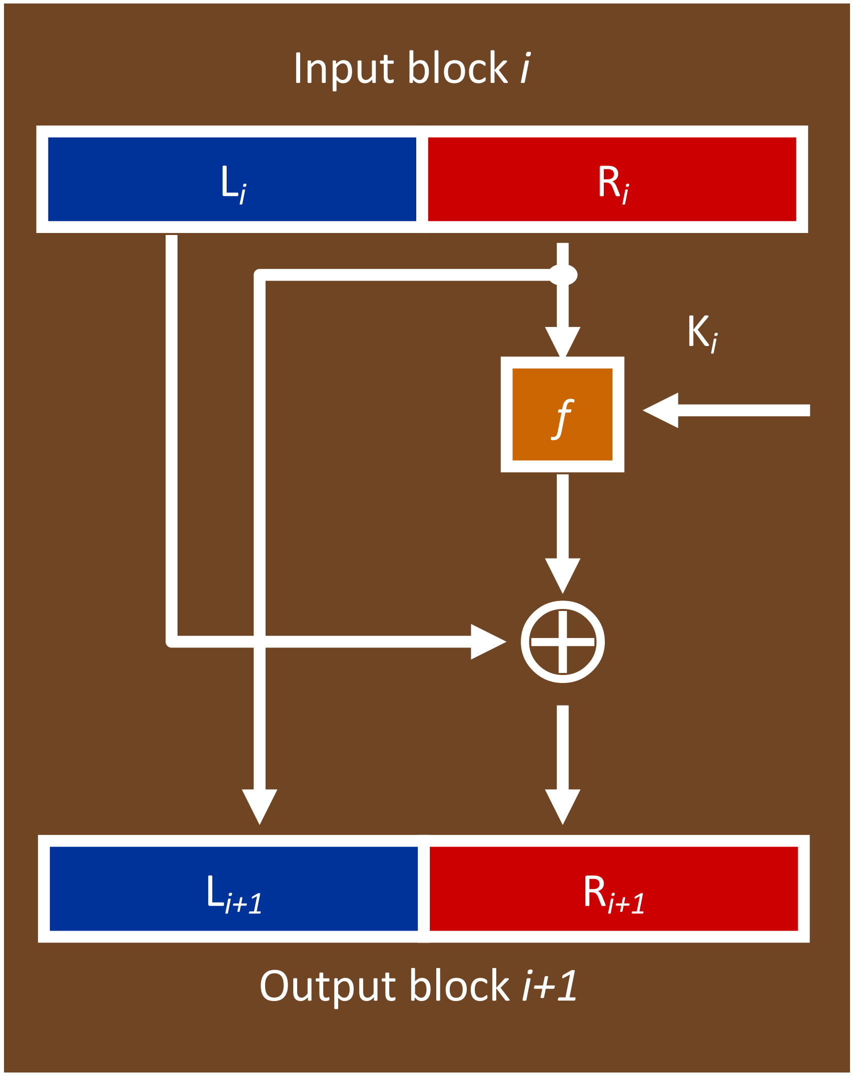
Feistel Ciphers

Overview

- Feistel Cipher has been a very influential "template" for designing a block cipher
- Major benefit: can do encryption and decryption with the same hardware
- Examples: DES, RC5

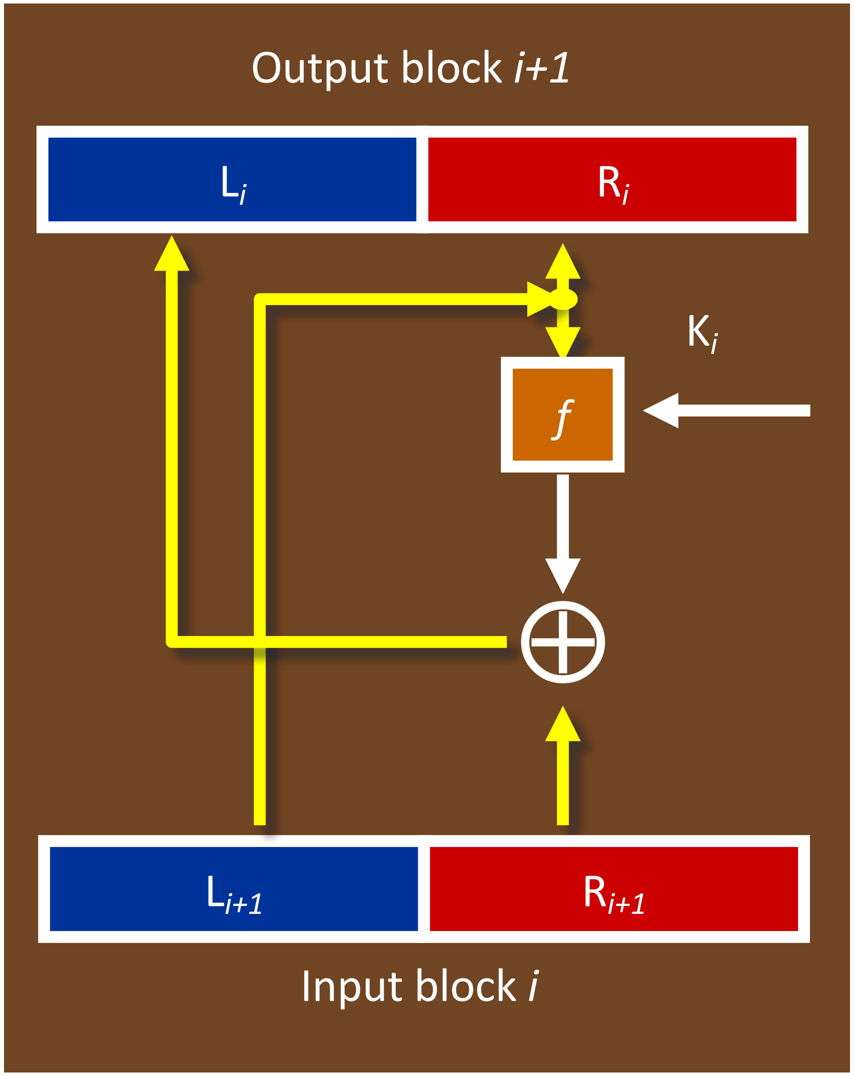
One "Round" of Feistel Encryption

1. Break input block *i* into left and right halves L_i and R_i
2. Copy R_i to create output half block L_{i+1}
3. Half block R_i and key K_i are "scrambled" by function *f*
4. XOR result with input half-block L_i to create output half-block R_{i+1}

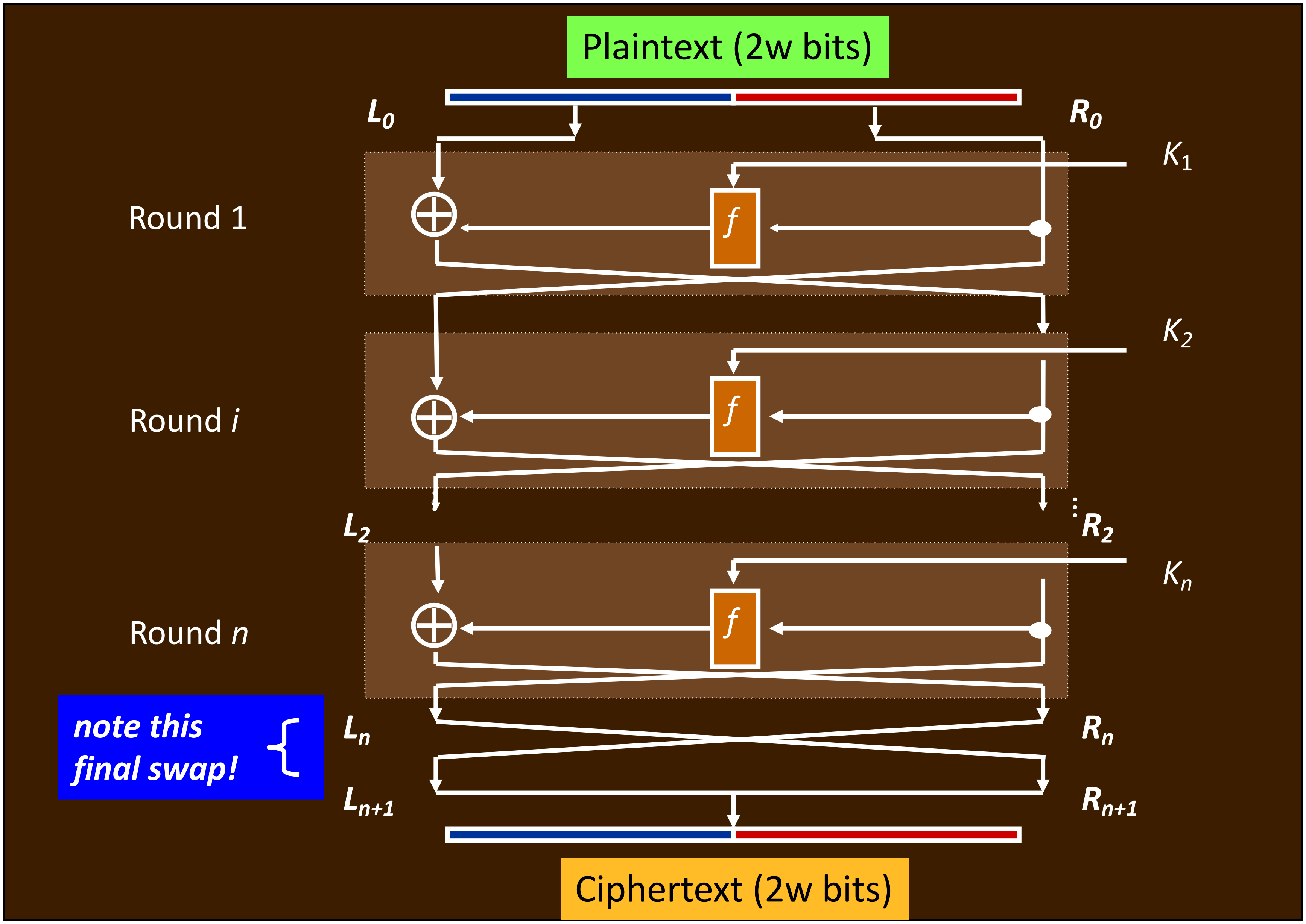


One "Round" of Feistel Decryption

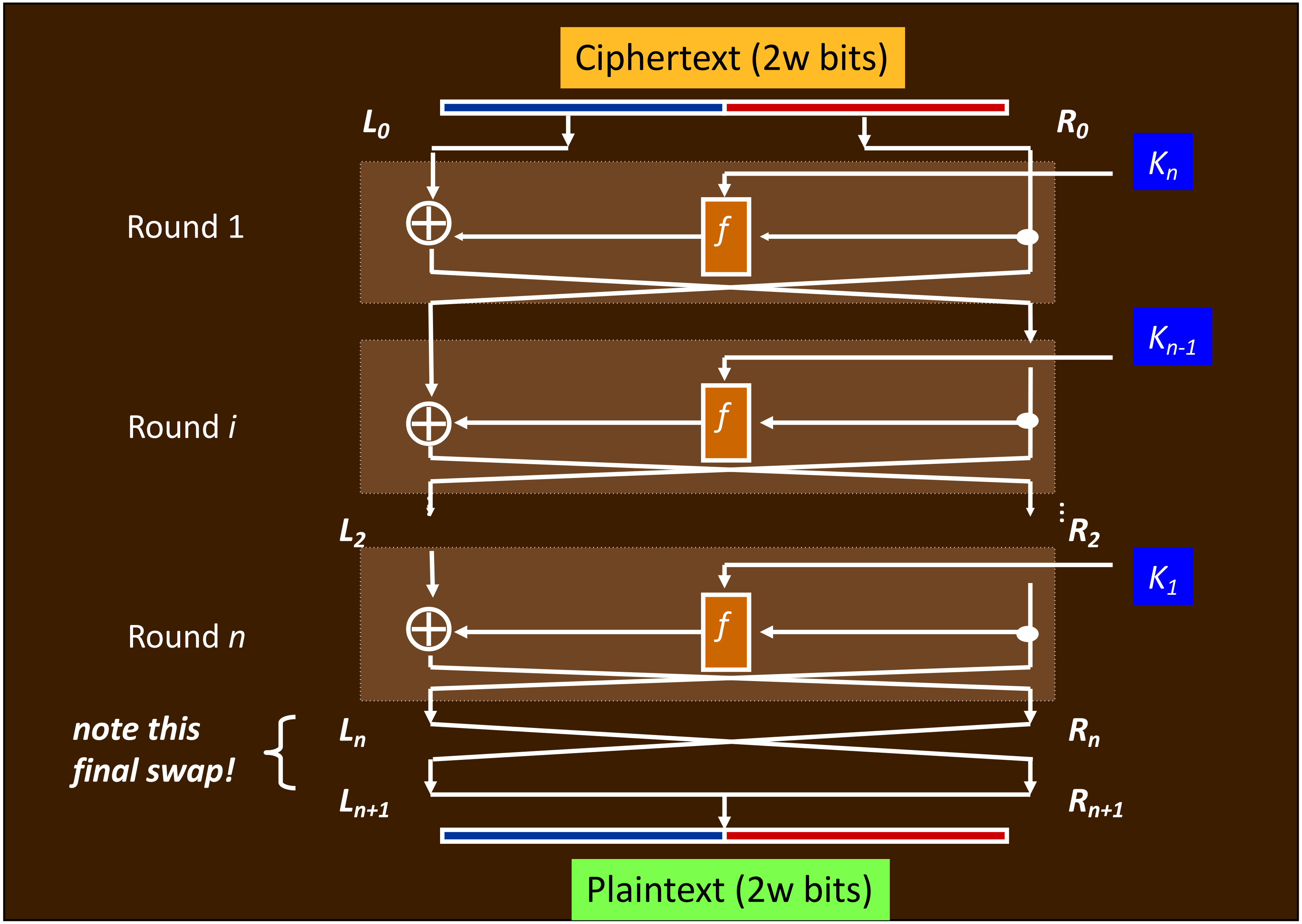
- Just reverse the arrows!



Complete Feistel Cipher: Encryption



Feistel Cipher: Decryption



Parameters of a Feistel Cipher

- Block size
- Key size
- Number of rounds
- Subkey generation algorithm
- “Scrambling” function *f*

Comments

- Decryption is same as encryption, only reversing the order in which round keys are applied
  - Reversability of Feistel cipher derives from reversability of XOR
- Function *f* can be anything
  - Hopefully something easy to compute
  - There is no need to invert *f*

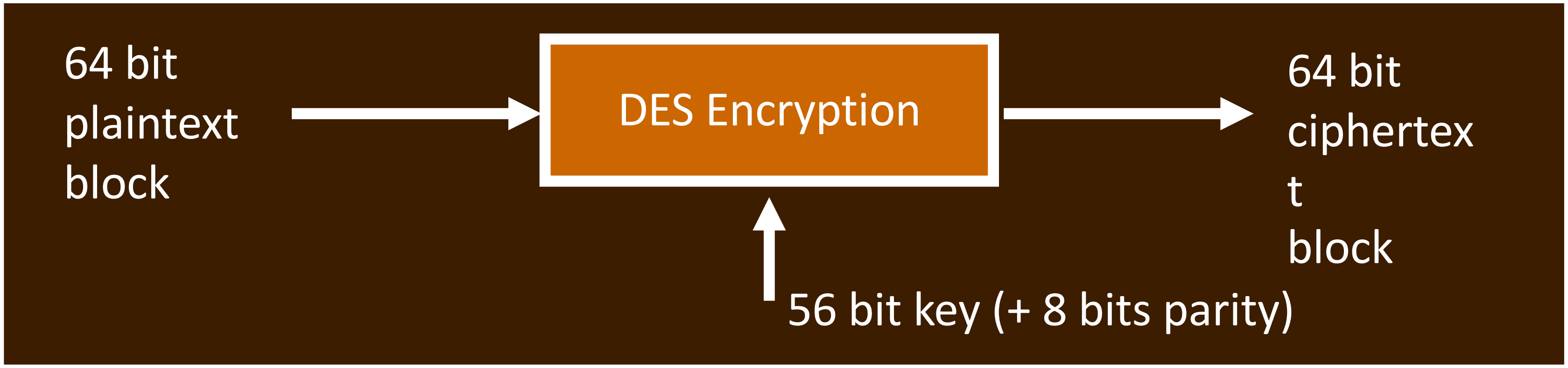
DES (Data Encryption Standard)

DES (Data Encryption Standard)

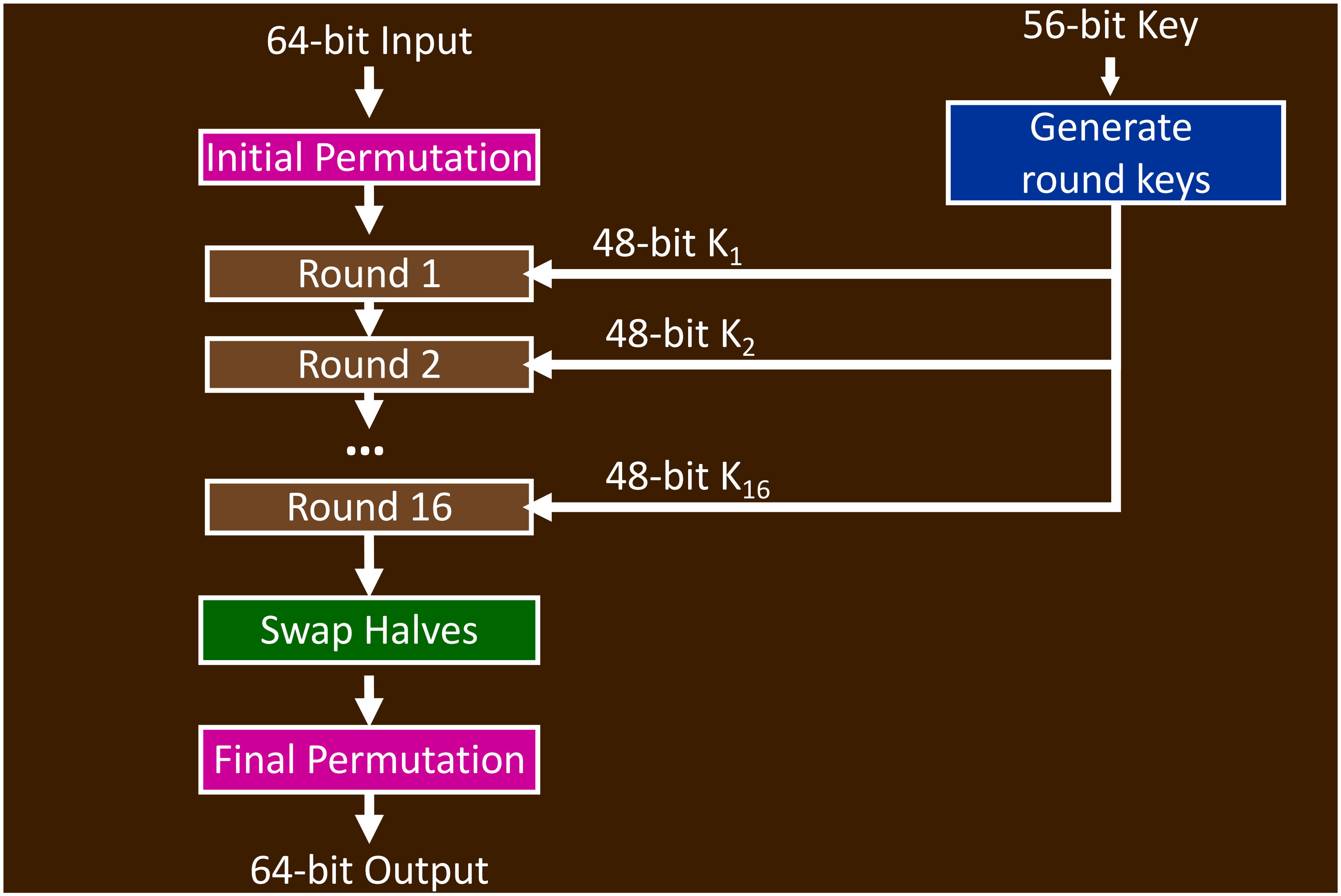
- Standardized in 1976 by NBS
  - proposed by IBM,
  - Feistel cipher
- Criteria (official)
  - provide high level of security
  - security must reside in key, not algorithm
  - not patented
  - must be exportable
  - efficient to implement in hardware
- Criteria (unofficial)
  - must be slow to execute in software
  - must be breakable by NSA :-)

DES Basics

- Blocks: 64 bit plaintext input,
  64 bit ciphertext output
- Rounds: 16
- Key: 64 bits
  - every 8th bit is a parity bit, so really <u>56</u> bits long

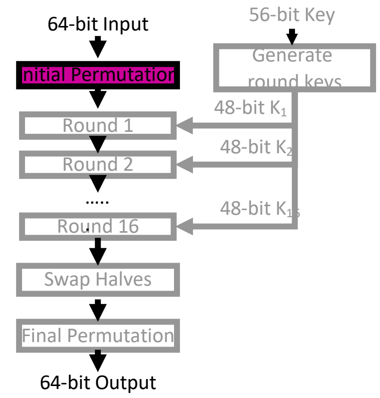


DES Top Level View



Initial and Final Permutations

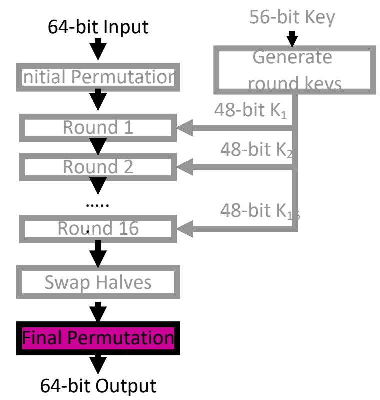
- Initial permutation given below
  - input bit #58→output bit #1, input bit #50→ output bit #2, …



58	50	42	34	26	18	10	2
60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6
64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1
59	51	43	35	27	19	11	3
61	53	45	37	29	21	13	5
63	55	47	39	31	23	15	7

Initial… (Cont'd)

- Final permutation is just inverse of initial permutation, i.e.,
  - input bit #1→ output bit #58
  - input bit #2→ output bit #50
  - …

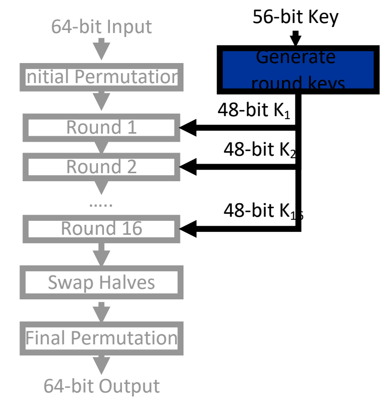


Initial… (Cont'd)

- Note #1: Initial Permutation is fully specified (independent of key)
  - therefore, does not improve security!
  - why needed?
- Note #2: Final Permutation is needed to make this a Feistel cipher
  - i.e., can use same hardware for both encryption and decryption

Key Generation: First Permutation

- First step: throw out 8 parity bits, then permute resulting 56 bits



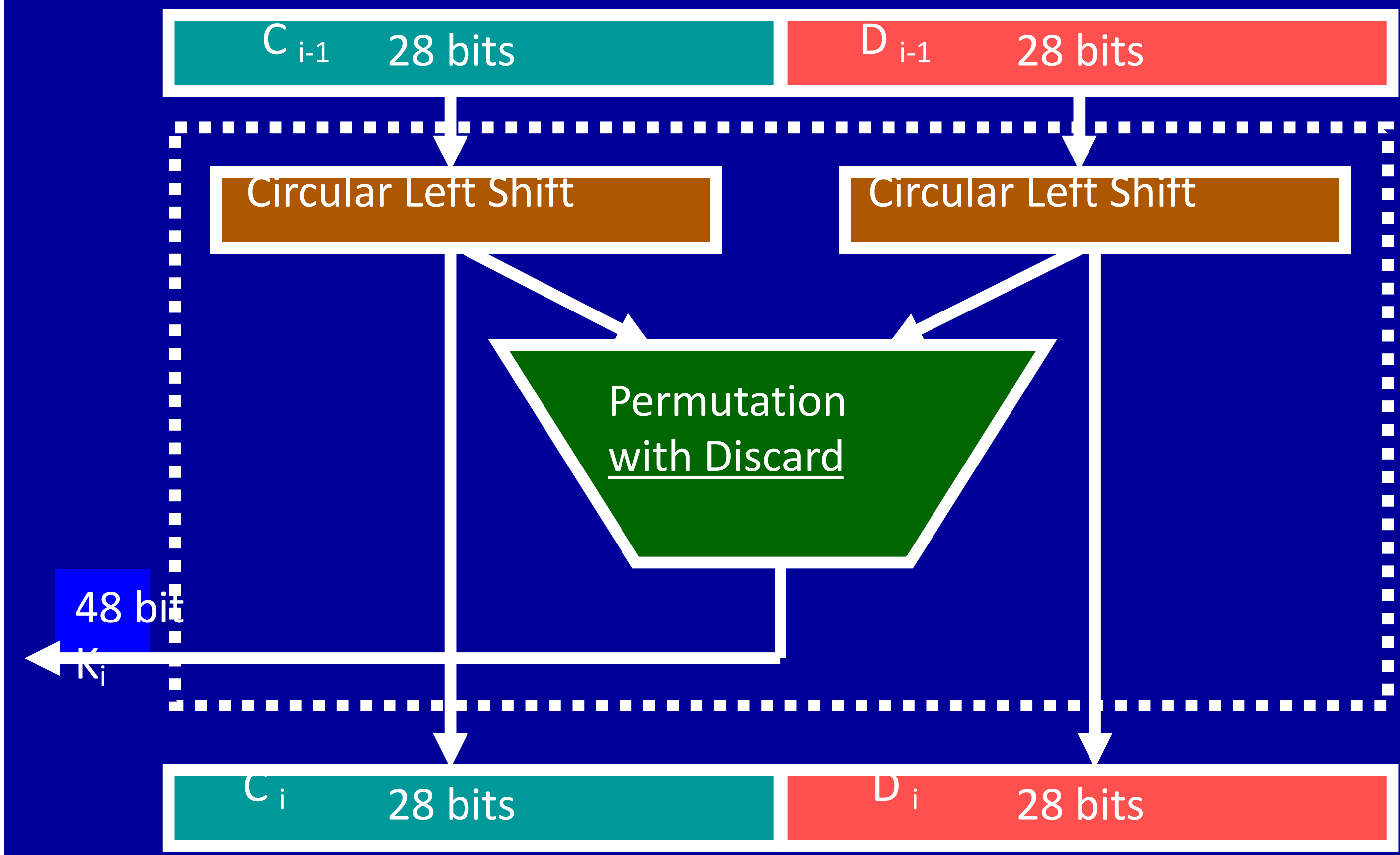
7 columns

8 rows

57	49	41	33	25	17	9
1	58	50	42	34	26	18
10	2	59	51	43	35	27
19	11	3	60	52	44	36
63	55	47	39	31	23	15
7	62	54	46	38	30	22
14	6	61	53	45	37	29
21	13	5	28	20	12	4

Parity bits left out: 8,16,24,…

KeyGen: Processing Per Round



Rounds i = 1,2,9,16:
left circular shift 1 bit
Other rounds:
left circular shift 2 bits

KeyGen: Permutation with Discard

- 28 bits → 24 bits, each half of key

Left half of K_i = permutation of C_i

14	17	11	24	1	5
3	28	15	6	21	10
23	19	12	4	26	8
16	7	27	20	13	2

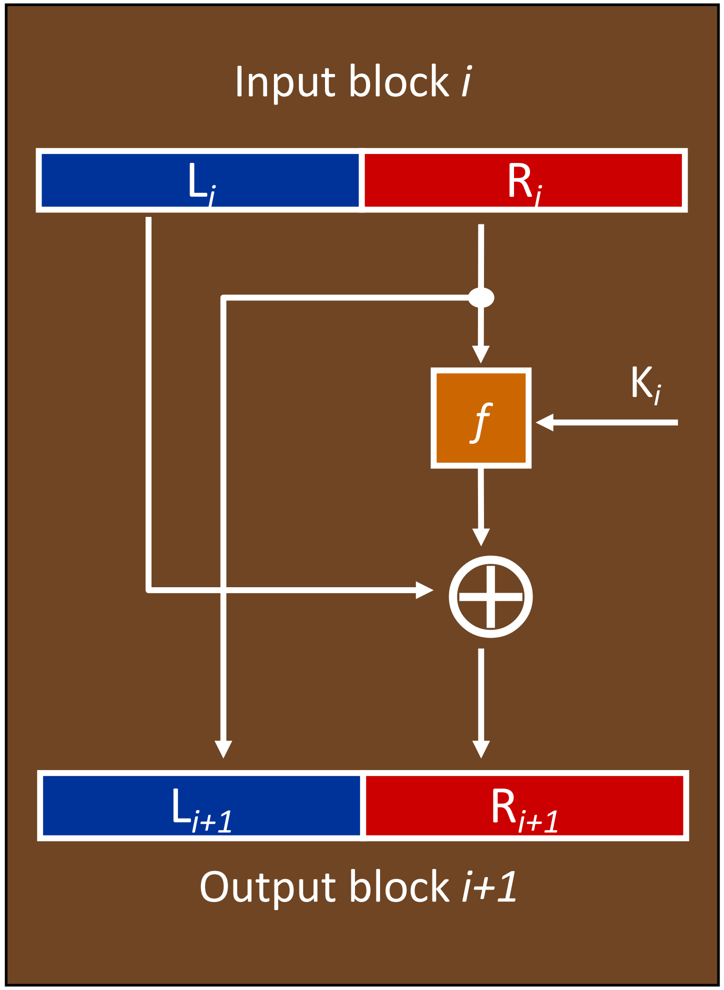
Bits left out:
9,18,22,25

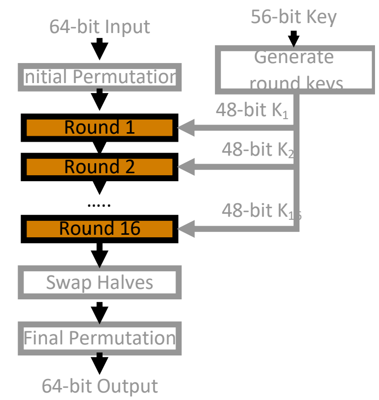
Right half of K_i = permutation of D_i

41	52	31	37	47	55
30	40	51	45	33	48
44	49	39	56	34	53
46	42	50	36	29	32

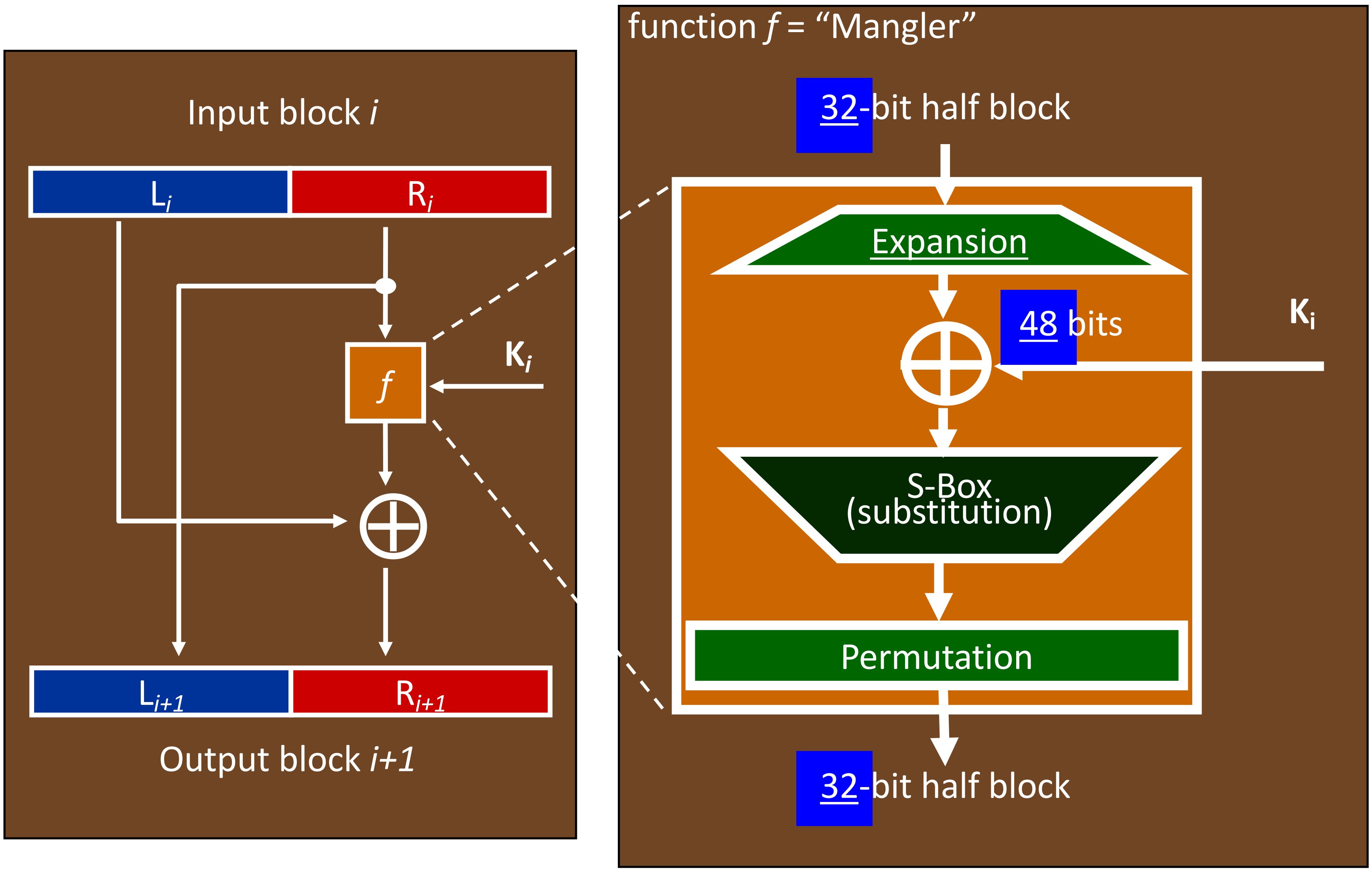
Bits left out:
35,38,43,54

One DES (Feistel) Round





DES Round: *f* (Mangler) Function



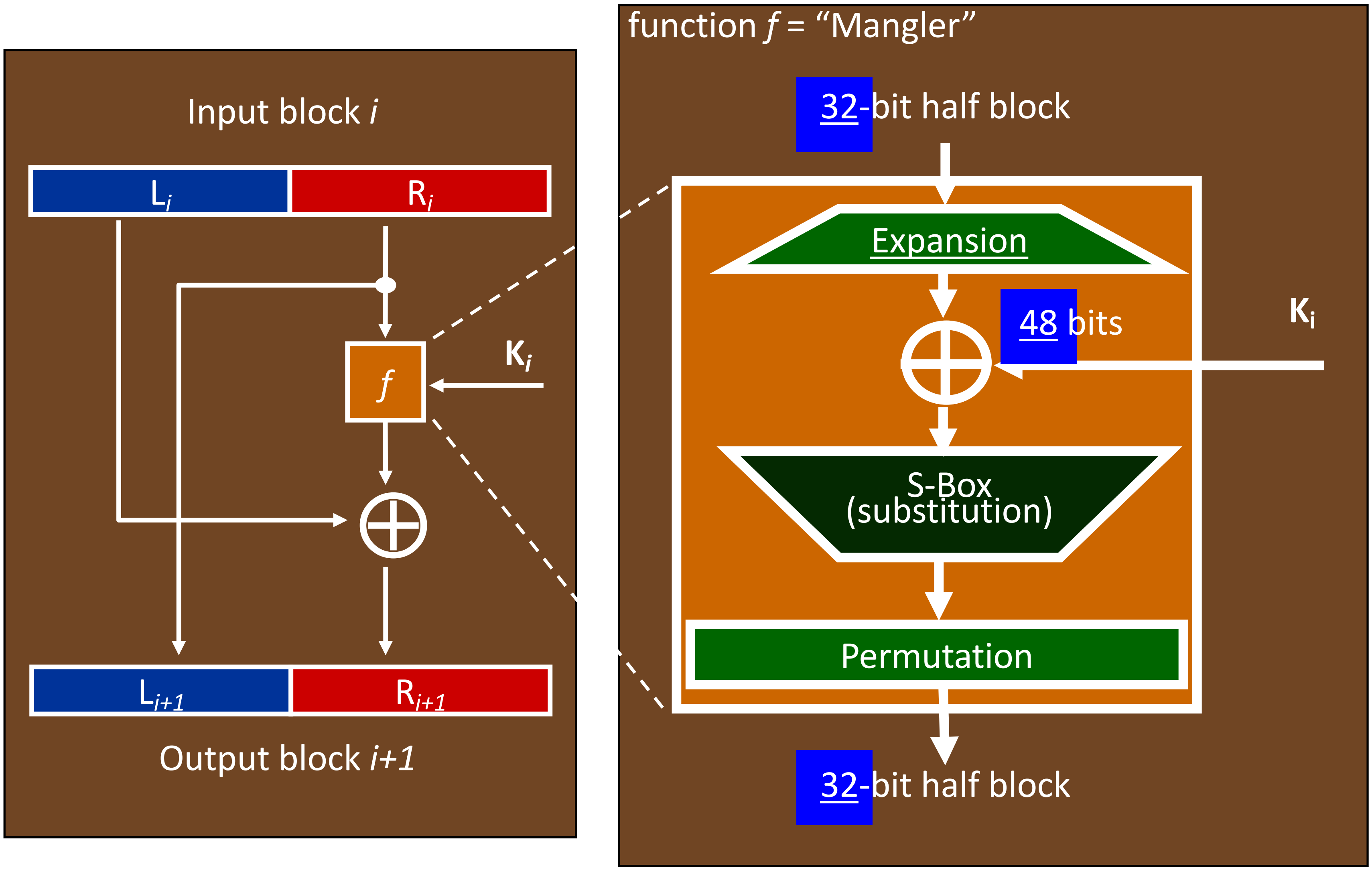
f: Expansion Function

- 32 bits → 48 bits

these bits are repeated

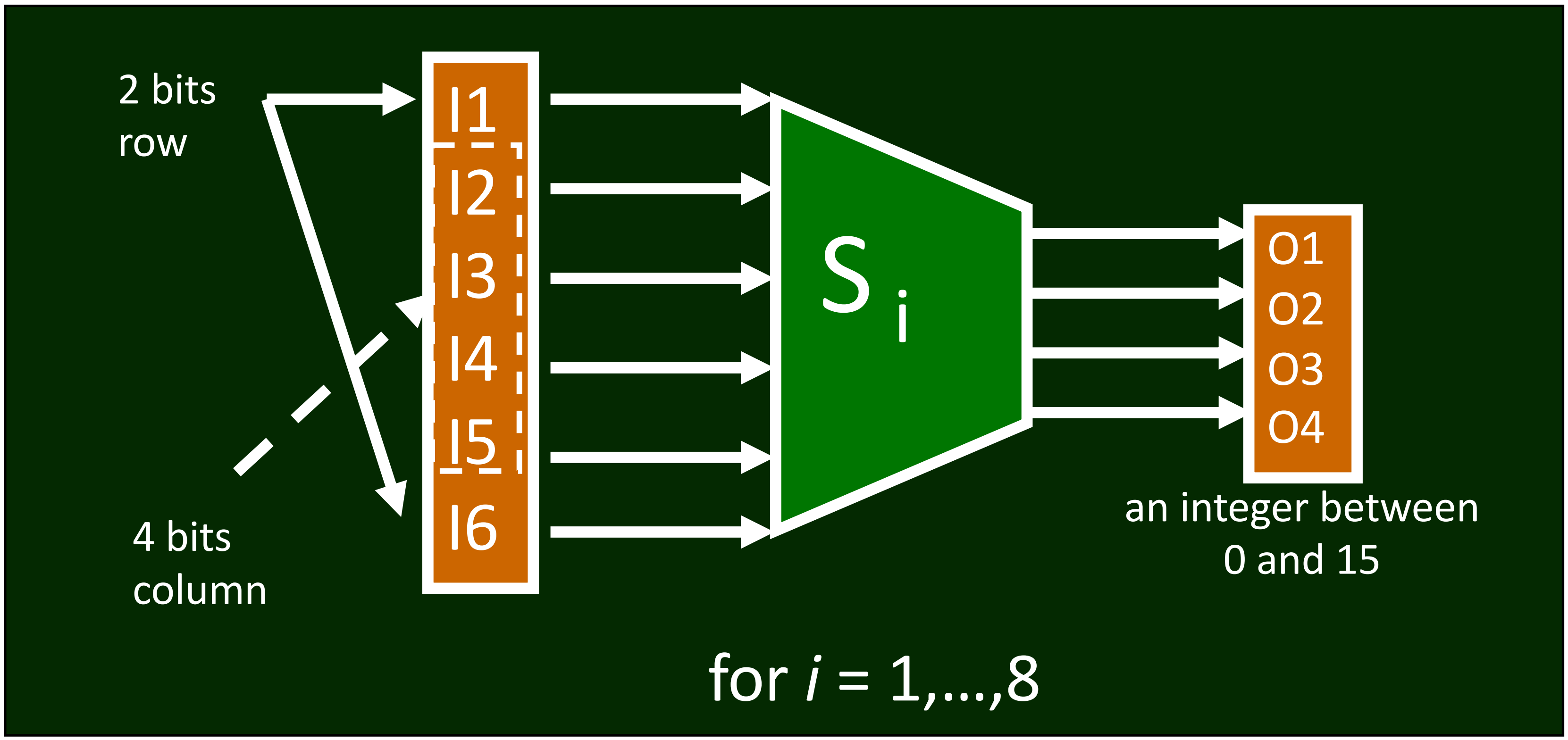
32	1	2	3	4	5
4	5	6	7	8	9
8	9	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	30	31	32	1

DES Round: *f* (Mangler) Function



f: S-Box (Substitute, Shrink)

- 48 bits → 32 bits
  - 6 bits are used to select a 4-bit substitution
  - Pre-defined lookup table for every 6 bits of input



f: S_1 (Substitution)

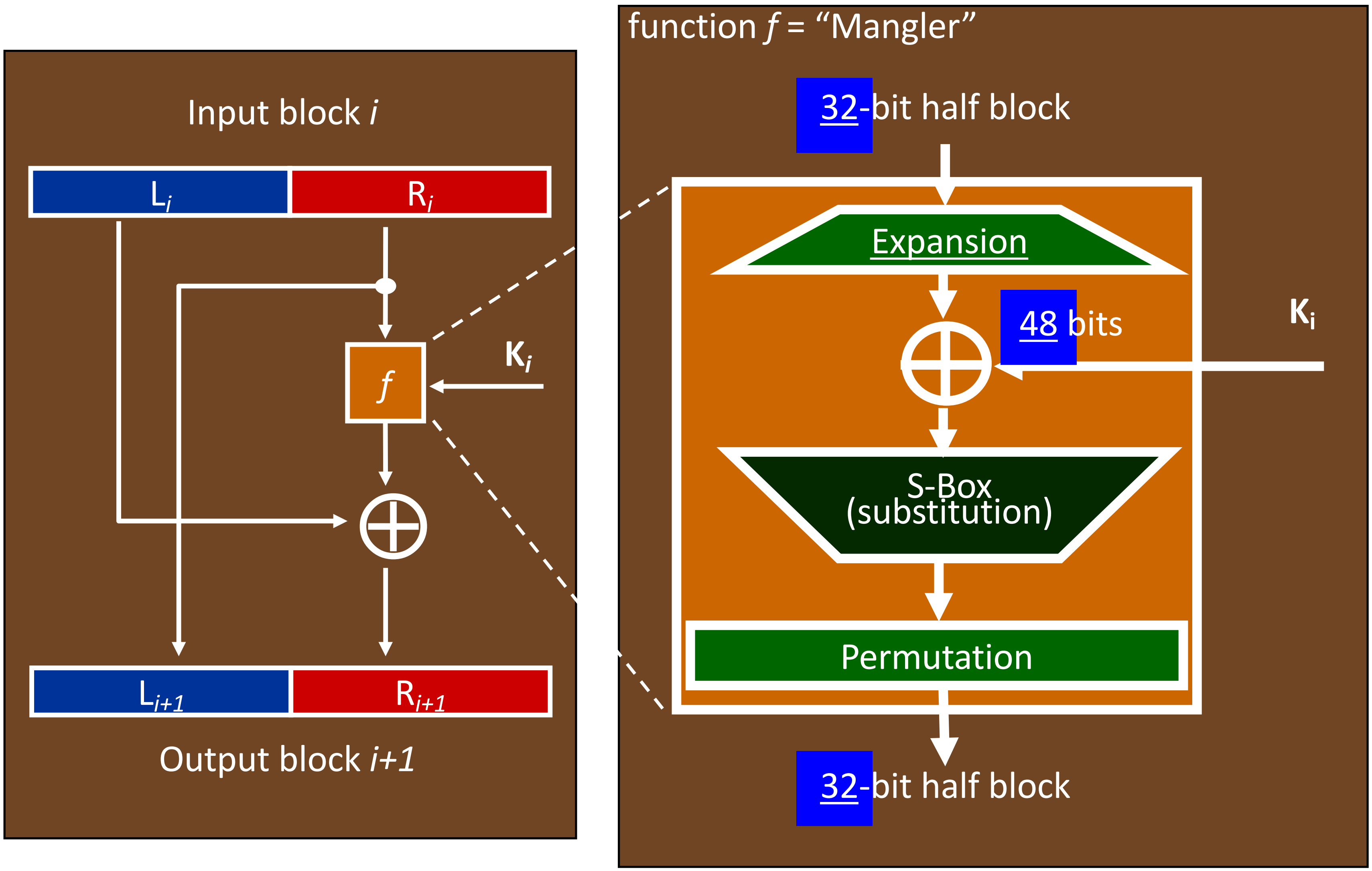
Each row and column contain different numbers

I1/I6 ↓ \ I2/I3/I4/I5 →	0	1	2	**3**	4	5	6	…	F
0	E	4	D	1	2	F	B		
1	0	F	7	4	E	2	D		
2	4	1	E	**8**	D	6	2		
3	F	C	8	2	4	9	1		

Example: input= 100110, output= 1000

for $S_2..S_8$ (and rest of S_1), see the textbook

DES Round: *f* (Mangler) Function



f: Permutation

- 32bits → 32bits

16	7	20	21
29	12	28	17
1	15	23	26
5	18	31	10
2	8	24	14
32	27	3	9
19	13	30	6
22	11	4	25

DES Implementation

- That's it!
- Operations
  - Permutation
  - Swapping halves
  - Substitution (S-box, table lookup)
  - Bit discard
  - Bit replication
  - Circular shift
  - XOR
- Hard to implement? HW: No, SW: Yes

DES Analysis

Good Design?

- "We don't know if
  - the particular details were well-chosen for strength,
  - whether someone flipped coins to construct the S-boxes,
  - or whether the details were chosen to have a weakness that could be exploited by the designers."

Issues for Block Ciphers

- Number of rounds should be large enough to make advanced attacks as expensive as exhaustive search for the key

Principles for S-Box Design

- S-box is the only non-linear part of DES
- Each row in the S-Box table should be a permutation of the possible output values
- Output of one S-box should affect other S-boxes in the following round

Desirable Property: Avalanche Effect

- Roughly: a small change in either the plaintext or the key should produce a big change in the ciphertext
- Better: any output bit should be inverted (flipped) with probability .5 if any input bit is changed
- f function
  - must be difficult to un-scramble
  - should achieve avalanche effect
  - output bits should be uncorrelated

DES Avalanche Effect: Example

- 2 plaintexts with 1 bit difference:

  0x0000000000000000 and

  0x8000000000000000

  encrypted using the same key:

  0x016B24621C181C32
- Resulting ciphertexts differ in 34 bits (out of 64)
- Similar results when keys differ by 1 bit

Example (cont'd)

- An experiment: number of rounds vs. number of bits difference

Round #	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bits changed	**1**	**6**	**21**	**35**	**39**	**34**	**32**	**31**	**29**	**42**	**44**	**32**	**30**	**30**	**26**	**29**	**34**

DES: Keys to Avoid Using

- "Weak keys": 4 keys with property

  K{K{m}} = m

- What's bad about that?
- These are keys which, after the first key permutation, are:
  - 28 0's followed by 28 0's
  - 28 0's followed by 28 1's
  - 28 1's followed by 28 0's
  - 28 1's followed by 28 1's

More Keys to Avoid!

- "Semi-weak keys": pairs of keys with the property

  $K_1\{K_2\{m\}\} = m$

- What's bad about that?
- These are keys which, after the first key permutation, are:

1. 28 0's followed by alternating 0's and 1's
2. 28 0's followed by alternating 1's and 0's

…

12. alternating 1's and 0's followed by alternating 1's and 0's

DES Key Size

- 56 bits is currently too small to resist brute force attacks using readily-available hardware
- 20 years ago it took $250,000 to build a machine that could crack DES in a few hours
- Now?

Cryptanalysis of DES

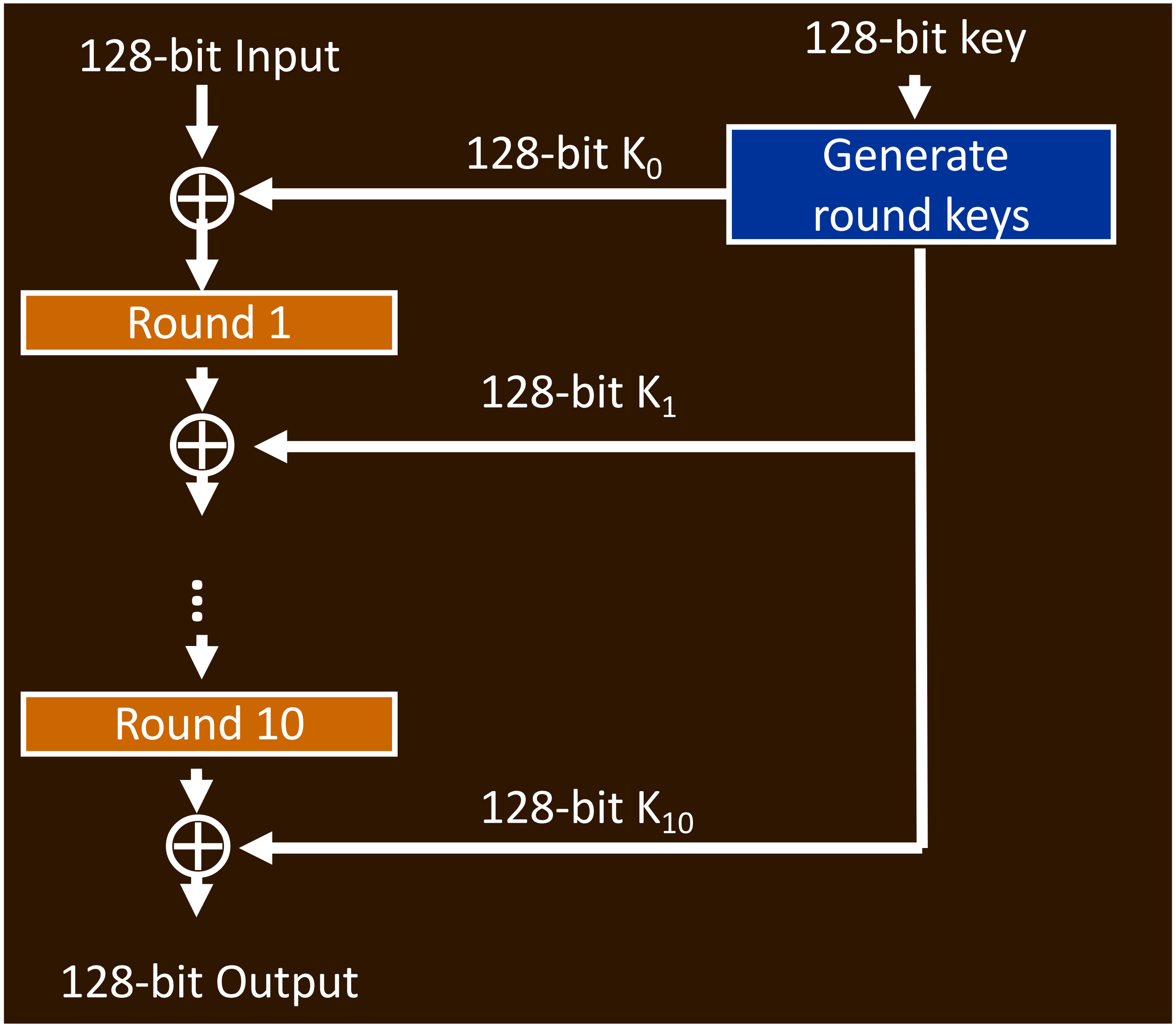
- Differential cryptanalysis exploits differences between encryptions of two different plaintext blocks
  - provides insight into possible key values
  - DES well designed to defeat differential analysis
- Linear cryptanalysis requires known plaintext / ciphertext pairs, analyzes relationships to discover key value
  - for DES, requires analyzing $O(2^{47})$ pairs
- No attacks on DES so far are significantly better than brute force attacks, for comparable cost

AES

Overview

- Selected from an open competition, organized by NSA
  - winner: Rijndael (pronounced “Rhine-dall”) algorithm, standardized as AES
- Some similarities to DES (rounds, round keys, alternate permutation+substitution)
  - but not a Feistel cipher
- Block size = 128 bits
- Key sizes = 128, 192, or 256 (Variable key lengths)
- Main criteria: secure, well justified, fast

AES-128 Overview



- Q1: What happens in each round?
- Q2: How are round keys generated?

AES-128 *State*

- Each plaintext block of 16 bytes is arranged as 4 columns of 4 bytes each

a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}

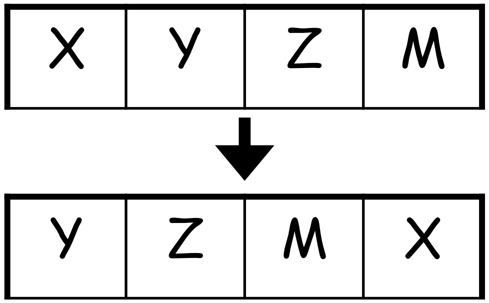
$\downarrow$

a_0	a_4	a_8	a_{12}
a_1	a_5	a_9	a_{13}
a_2	a_6	a_{10}	a_{14}
a_3	a_7	a_{11}	a_{15}

(Padding necessary for messages not a multiple of 16 bytes)

High-level View: One AES-128 Round

1. Apply S-box function to each byte of the state (i.e., 16 substitutions)
2. Rotate…
   - (row 0 of state is unchanged)
   - row 1 of the state left 1 column
   - row 2 of the state left 2 columns
   - row 3 of the state left 3 columns



3. Apply MixColumn function to each column of state
   - last round omits this step

AES-128 Decryption (Conceptual)

- Run cipher in reverse, with inverse of each operation replacing the encryption operations
- Inverse operations:
  - XOR is its own inverse
  - inverse of S-box is just the inverse table
  - inverse of rotation in one direction is rotation in other direction
  - inverse of MixColumn is just the inverse table

AES Decryption (Actual)

- Run cipher in forward direction, except…
  - use inverse operations
  - apply round keys in reverse order
  - apply InvMixColumn to round keys K1..K9
- Decryption takes more memory and cycles encryption
  - can only partially reuse hardware for encryption

AES Assessment

- Speed: about 16 clock cycles/byte on modern 32-bit CPUs
  - 200 MByte/s on a PC, no special hardware!
- No known successful attacks on full AES
  - best attacks work on 7–9 rounds (out of 10–14 rounds)
- Clean design
- For brute force attacks, AES-128 will take $4 * 10^{21}$ X (= 2^{72}) more effort than DES

Attacks on AES

Differential Cryptanalysis: based on how differences in inputs correlate with differences in outputs

- greatly reduced due to high number of rounds

Linear Cryptanalysis: based on correlations between input and output

- S-Box & MixColumns are designed to frustrate Linear Analysis

Side Channel Attacks: based on peculiarities of the implementation of the cipher

Side Channel Attacks

Timing Attacks: measure the time it takes to do operations

- some operations, with some operands, are much faster than other operations, with other operand values
- provides clues about what internal operations are being performed, and what internal data values are being produced

Power Attacks: measures power to do operations

- changing one bit requires considerably less power than changing many bits in a byte

Summary

- Secret key crypto is (a) good quality, (b) faster to compute than public key crypto, and (c) the most widely used crypto
- DES strong enough for non-critical applications, but triple-DES is better
- AES even better (stronger and much faster), has versions with 128-, 192-, and 256-bit keys
- Secret key crypto requires “out-of-band”, bilateral key negotiation/agreement