CSCI 454/554 Computer and Network Security

Topic 3.1 Secret Key Cryptography – Algorithms

Outline

- Introductory Remarks
- Feistel Cipher
- DES
- AES

Introduction

Secret Keys or Secret Algorithms ?

- "Security by obscurity"
  - "hide" the details of the algorithms
  - drawback: hard to keep secret if cipher is used widely, or implementation can be reverse engineered
- Alternative: publish the algorithms
  - fewer vulnerabilities will result if many smart people try and fail to break the cipher
  - security of the cipher depends on the secrecy of the keys, instead

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Secrets? (Cont'd)

- Commercial world relies upon standardized, public algorithms, and secret keys
- Government tends to also rely on secret algorithms

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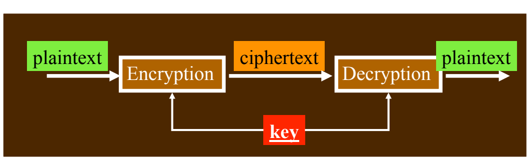
Secret Key Cryptography



- 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

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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

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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?

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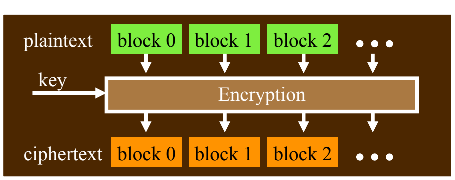
Generic Block Encryption

- 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*?



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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

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Notation

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

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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

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Exploiting the Principles

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- Idea: use multiple, alternating permutations and substitutions, 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

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Secret Key… (Cont'd)

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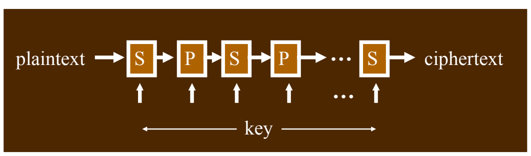
- Basic technique used in secret key ciphers: multiple applications of alternating substitutions and permutations



Well-known examples: DES, AES

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Basic Form of Modern Block Ciphers

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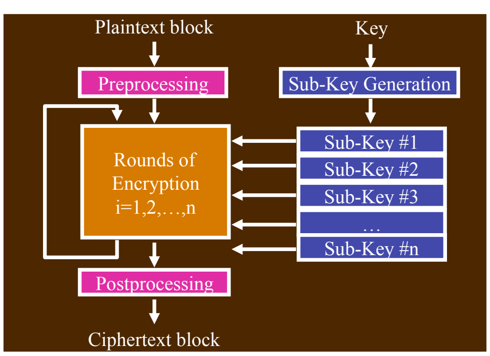

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Feistel Ciphers

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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

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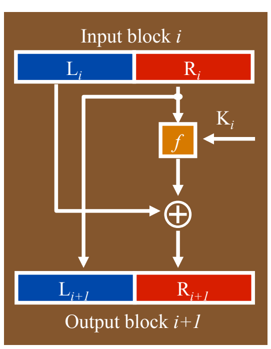
One "Round" of Feistel Encryption

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}



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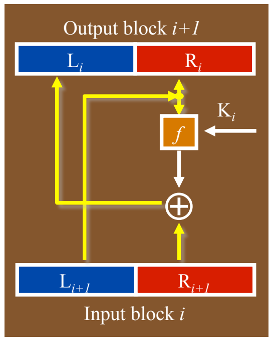
One "Round" of Feistel Decryption

- Just reverse the arrows!



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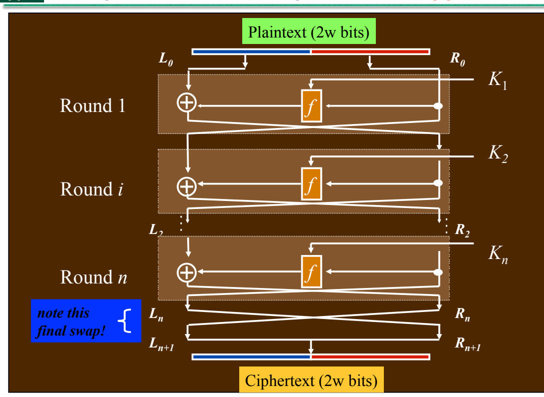
Complete Feistel Cipher: Encryption



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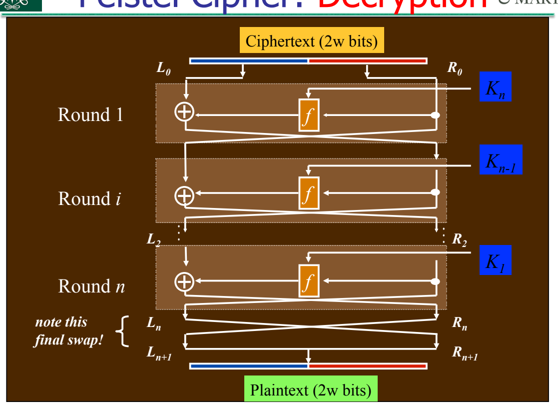
Feistel Cipher: Decryption



Parameters of a Feistel Cipher

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

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Comments

- Decryption is the 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*

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DES (Data Encryption Standard)

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DES (Data Encryption Standard)

- Standardized in 1976 by NBS (now NIST)
  - 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

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DES… (Cont'd)

- Criteria (unofficial)
  - must be slow to execute in software
  - must be breakable by NSA :-)

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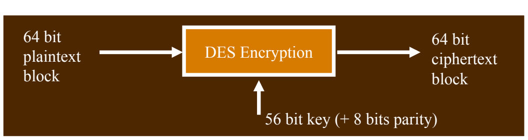
DES Basics

- Blocks: 64 bit plaintext input,
  64 bit ciphertext output
- Rounds: 16
- Key: 64 bits
  - every 8^{th} bit is a parity bit, so really 56 bits long



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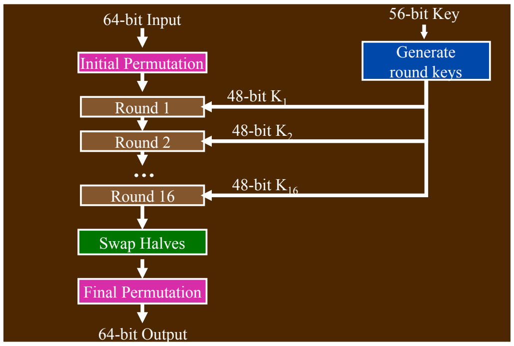
DES Top Level View



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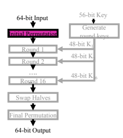
Initial and Final Permutations

- 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



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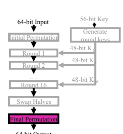
Initial… (Cont'd)

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



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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

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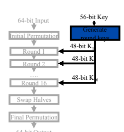
Key Generation: First Permutation

- 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,…

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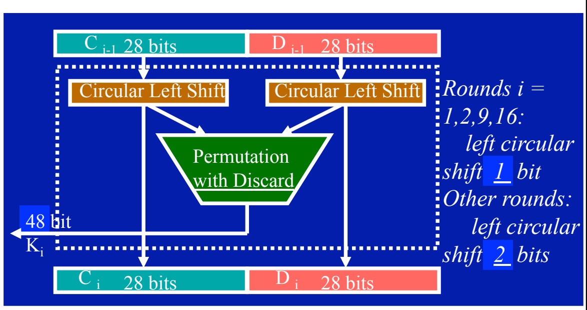
KeyGen: Processing Per Round



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KeyGen: Permutation with Discard

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- 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

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One DES (Feistel) Round

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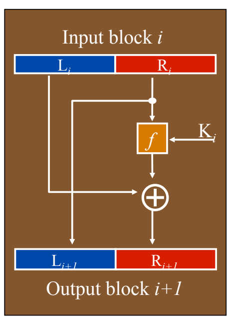

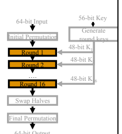

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DES Round: *f* (Mangler) Function

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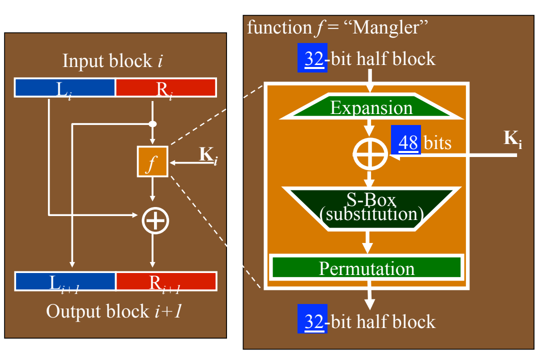

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f: Expansion Function

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- 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

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f: S-Box (Substitute, Shrink)

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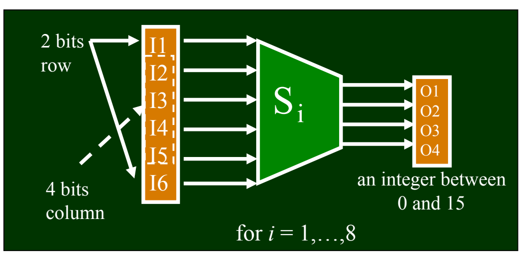
- 48 bits ➔ 32 bits
  - 48 bit is broken into eight 6-bit chunks.
  - 6 bits are used to select a 4-bit substitution
  - i.e., for every output, there are four inputs that map to it



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f: S_1 (Substitution)

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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

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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

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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

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DES Analysis

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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."

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Issues for Block Ciphers

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

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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

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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 0.5 if any input bit is changed
- *f* function
  - must be difficult to un-scramble
  - should achieve avalanche effect
  - output bits should be uncorrelated

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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

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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

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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

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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

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DES Key Size

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

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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

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AES (Advanced Encryption Standard)

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Overview

- Selected from an open competition, organized by NSA
  - winner: Rijndael algorithm, standardized as AES
  - A short history: http://www.moserware.com/2009/09/stick-figure-guide-to-advanced.html
- 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
- Main criteria: secure, well justified, fast

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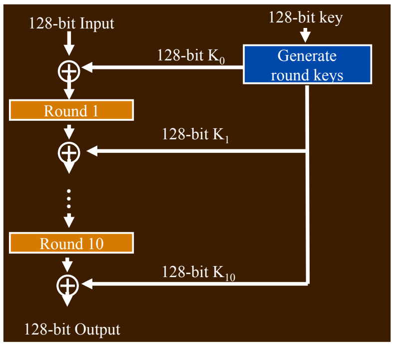
AES-128 Overview



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

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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}

↓

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)

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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 shifts left 1 column
   - row 2 of the state shifts left 2 columns
   - row 3 of the state shifts left 3 columns
3. Apply MixColumn function to each column of state
   - last round omits this step

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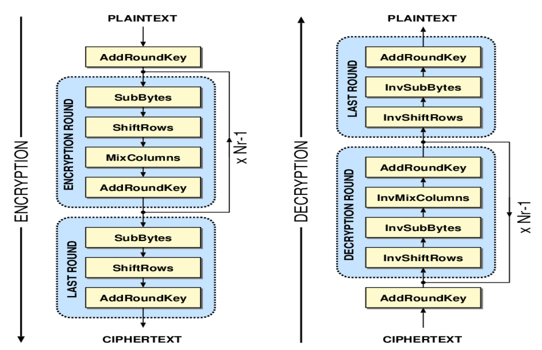
AES Encryption/Decryption



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Round Step 1. AES S-Box

- Each byte of state is replaced by a value from following table
  - eg. byte with value 0x95 is replaced by byte in row 9 column 5, which has value 0x2A

	Y															
X	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	63	7c	77	7b	f2	6b	6f	c5	30	1	67	2b	fe	d7	ab	76
1	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
2	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
3	4	c7	23	c3	18	96	5	9a	7	12	80	e2	eb	27	b2	75
4	9	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	2f	84
5	53	d1	0	ed	20	fc	b1	5b	6a	cb	be	39	4a	4c	58	cf
6	d0	ef	aa	fb	43	4d	33	85	45	f9	2	7f	50	3c	9f	a8
7	51	a3	40	8f	92	9d	38	f5	bc	b6	da	21	10	ff	f3	d2
8	cd	0c	13	ec	5f	97	44	17	c4	a7	7e	3d	64	5d	19	73
9	60	81	4f	dc	22	2a	90	88	46	ee	b8	14	de	5e	0b	db
a	e0	32	3a	0a	49	6	24	5c	c2	d3	ac	62	91	95	e4	79
b	e7	c8	37	6d	8d	d5	4e	a9	6c	56	f4	ea	65	7a	ae	8
c	ba	78	25	2e	1c	a6	b4	c6	e8	dd	74	1f	4b	bd	8b	8a
d	70	3e	b5	66	48	3	f6	0e	61	35	57	b9	86	c1	1d	9e
e	e1	f8	98	11	69	d9	8e	94	9b	1e	87	e9	ce	55	28	df
f	8c	a1	89	0d	bf	e6	42	68	41	99	2d	0f	b0	54	bb	16

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S-Box (Cont'd)

The S-Box is what makes AES a non-linear cipher

For every value of b there is a unique value for b'

- It is faster to use a substitution table (and easier).

$$\begin{bmatrix} b'_0 \\ b'_1 \\ b'_2 \\ b'_3 \\ b'_4 \\ b'_5 \\ b'_6 \\ b'_7 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}$$

$x = b^{-1}$ in $GF(2^8)$, i.e., x is the inverse of byte b

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S-Box Example

- The S-Box is what makes AES a non-linear cipher

State

50	10	D0	81
60	20	4A	93
70	30	E1	A1
00	C0	F7	AF

→

Sbox(50)	Sbox(10)	Sbox(D0)	Sbox(81)
Sbox(60)	Sbox(20)	Sbox(4A)	Sbox(93)
Sbox(70)	Sbox(30)	Sbox(E1)	Sbox(A1)
Sbox(00)	Sbox(C0)	Sbox(F7)	Sbox(AF)

↓

After SubBytes

53	CA	70	0C
D0	B7	D6	DC
51	04	F8	32
63	BA	68	79

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Round Step 2. Rotate (Example)

Before Shift Rows

53	CA	70	0C
D0	B7	D6	DC
51	04	F8	32
63	BA	68	79

→

After Shift Rows

53	CA	70	0C
B7	D6	DC	D0
F8	32	51	04
79	63	BA	68

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Round Step 3. MixColumn Function

- Applied to each column of the state
- For each column, each byte $a_i \ldots a_{i+3}$ of the column is used to look up four 4-byte intermediate columns $t_i \ldots t_{i+3}$ from a table (next slide)
- The intermediate columns $t_i \ldots t_{i+3}$ are then combined (next slide + 1):
  - rotate vertically so top octet of t_i is in the same row as input octet (a_i)
  - XOR the four rotated columns together

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MixColumn… (Cont'd)

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- Part of the MixColumn table:

right (low-order) nibble (4 bits)

left (high-order) nibble (4 bits)

	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	00 00 00 00	02 01 01 03	04 02 02 06	06 03 03 05	08 04 04 0c	0a 05 05 0f	0c 06 06 0a	0e 07 07 09	10 08 08 18	12 09 09 1b	14 0a 0a 1e	16 0b 0b 1d	18 0c 0c 14	1a 0d 0d 17	1c 0e 0e 12	1e 0f 0f 11
1	20 10 10 30	22 11 11 33	24 12 12 36	26 13 13 35	28 14 14 3c	2a 15 15 3f	2c 16 16 3a	2e 17 17 39	30 18 18 28	32 19 19 2b	34 1a 1a 2e	36 1b 1b 2d	38 1c 1c 24	3a 1d 1d 27	3c 1e 1e 22	3e 1f 1f 21
2	40 20 20 60	42 21 21 63	44 22 22 66	46 23 23 65	48 24 24 6c	4a 25 25 6f	4c 26 26 6a	4e 27 27 69	50 28 28 78	52 29 29 7b	54 2a 2a 7e	56 2b 2b 7d	58 2c 2c 74	5a 2d 2d 77	5c 2e 2e 72	5e 2f 2f 71
	60	62	64	66	68	6a	6c	6e	70	72	74	76	78	7a	7c	7e
d	bb d0 d0 6b	b9 d1 d1 68	bf d2 d2 6d	bd d3 d3 6e	b3 d4 d4 67	b1 d5 d5 64	b7 d6 d6 61	b5 d7 d7 62	ab d8 d8 73	a9 d9 d9 70	af da da 75	ad db db 76	a3 dc dc 7f	a1 dd dd 7c	a7 de de 79	a5 df df 7a
e	db e0 e0 3b	d9 e1 e1 38	df e2 e2 3d	dd e3 e3 3e	d3 e4 e4 37	d1 e5 e5 34	d7 e6 e6 31	d5 e7 e7 32	cb e8 e8 23	c9 e9 e9 20	cf ea ea 25	cd eb eb 26	c3 ec ec 2f	c1 ed ed 2c	c7 ee ee 29	c5 ef ef 2a
f	fb f0 f0 0b	f9 f1 f1 08	ff f2 f2 0d	fd f3 f3 0e	f3 f4 f4 07	f1 f5 f5 04	f7 f6 f6 01	f5 f7 f7 02	eb f8 f8 13	e9 f9 f9 10	ef fa fa 15	ed fb fb 16	e3 fc fc 1f	e1 fd fd 1c	e7 fe fe 19	e5 ff ff 1a

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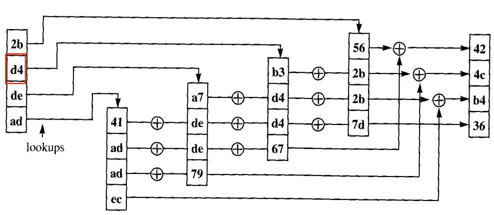
MixColumn… (Cont'd)

WILLIAM & MARY

- Example



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Generating Round Keys in AES-128

WILLIAM & MARY

The key (16 bytes) is arranged in 4 columns of 4 rows, as for the input (plaintext) block)

Deriving the round keys makes use of a table of constants:

Removes symmetry and linearity from key expansion

Round i	Constant c_i
1	0x01
2	0x02
3	0x04
4	0x08
5	0x10
6	0x20
7	0x40
8	0x80
9	0x1b
10	0x36

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Round Keys… (Cont'd)

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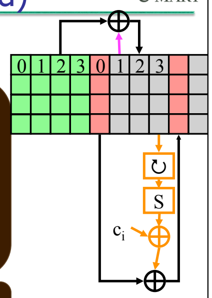
For i^{th} round of keys, i = 1..10

for column index j = 0
  temp = column 3 of
    $(i-1)^{th}$ (previous) round
  rotate temp upward one byte
  S-Box transform each byte
    of temp
  XOR first byte of temp with c_i

for column index j = 1..3
  temp = column j-1 of i^{th} (this) round

result = temp XOR j^{th} column of key round i-1



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Round Keys… (Cont'd)

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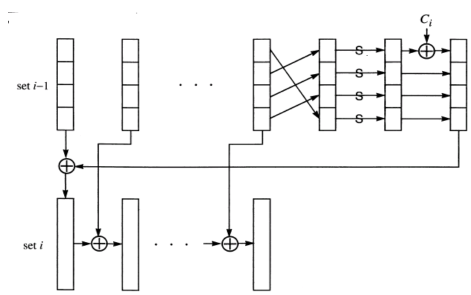

Figure 3-30. Rijndael key expansion, iteration step, $N_k \leq 6$

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Key Expansion Rationale

WILLIAM & MARY

- Designed to resist known attacks
- Design criteria include
  - knowing part of the key doesn't make it easy to find entire key
  - key expansion must be invertible, but enough non-linearity to hinder analysis
  - should be fast to compute, simple to describe and analyze
  - key bits should be diffused into the round keys

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Mathematics

AES Operates on the binary field $GF(2^8)$

- this can be represented as a polynomial $b(x)$ with binary coefficients $b \in \{0,1\}$:

$$b_7x^7 + b_6x^6 + b_5x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_1x + b_0$$

Multiplication in $GF(2^8)$ consists of multiplying two polynomials modulo an irreducible polynomial of degree 8

- AES uses the following irreducible polynomial

$$m(x) = x^8 + x^4 + x^3 + x + 1$$

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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 *(next slide)*
  - inverse of rotation in one direction is rotation in other direction
  - inverse of MixColumn is just the inverse table *(next slide + 1)*

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Inverse S-Box

		Y															
		0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
X	0	52	9	6a	d5	30	36	a5	38	bf	40	a3	9e	81	f3	d7	fb
	1	7c	e3	39	82	9b	2f	ff	87	34	8e	43	44	c4	de	e9	cb
	2	54	7b	94	32	a6	c2	23	3d	ee	4c	95	0b	42	fa	c3	4e
	3	8	2e	a1	66	28	d9	24	b2	76	5b	a2	49	6d	8b	d1	25
	4	72	f8	f6	64	86	68	98	16	d4	a4	5c	cc	5d	65	b6	92
	5	6c	70	48	50	fd	ed	b9	da	5e	15	46	57	a7	8d	9d	84
	6	90	d8	ab	0	8c	bc	d3	0a	f7	e4	58	5	b8	b3	45	6
	7	d0	2c	1e	8f	ca	3f	0f	2	c1	af	bd	3	1	13	8a	6b
	8	3a	91	11	41	4f	67	dc	ea	97	f2	cf	ce	f0	b4	e6	73
	9	96	ac	74	22	e7	ad	35	85	e2	f9	37	e8	1c	75	df	6e
	a	47	f1	1a	71	1d	29	c5	89	6f	b7	62	0e	aa	18	be	1b
	b	fc	56	3e	4b	c6	d2	79	20	9a	db	c0	fe	78	cd	5a	f4
	c	1f	dd	a8	33	88	7	c7	31	b1	12	10	59	27	80	ec	5f
	d	60	51	7f	a9	19	b5	4a	0d	2d	e5	7a	9f	93	c9	9c	ef
	e	a0	e0	3b	4d	ae	2a	f5	b0	c8	eb	bb	3c	83	53	99	61
	f	17	2b	4	7e	ba	77	d6	26	e1	69	14	63	55	21	0c	7d

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InvMixColumn

right (low-order) nibble (4 bits)

left (high-order) nibble (4 bits)

	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	00	0e	1c	12	38	36	24	2a	70	7e	6c	62	48	46	54	5a
	00	09	12	1b	24	2d	36	3f	48	41	5a	53	6c	65	7e	77
	00	0d	1a	17	34	39	2e	23	68	65	72	7f	5c	51	46	4b
	00	0b	16	1d	2c	27	3a	31	58	53	4e	45	74	7f	62	69
1	e0	ee	fc	f2	d8	d6	c4	ca	90	9e	8c	82	a8	a6	b4	ba
	90	99	82	8b	b4	bd	a6	af	d8	d1	ca	c3	fc	f5	ee	e7
	d0	dd	ca	c7	e4	e9	fe	f3	b8	b5	a2	af	8c	81	96	9b
	b0	bb	a6	ad	9c	97	8a	81	e8	e3	fe	f5	c4	cf	d2	d9
2	db	d5	c7	c9	e3	ed	ff	f1	ab	a5	b7	b9	93	9d	8f	81
	3b	32	29	20	1f	16	0d	04	73	7a	61	68	57	5e	45	4c
	bb	b6	a1	ac	8f	82	95	98	d3	de	c9	c4	e7	ea	fd	f0
	7b	70	6d	66	57	5c	41	4a	23	28	35	3e	0f	04	19	12
d	0c	02	10	1e	34	3a	28	26	7c	72	60	6e	44	4a	58	56
	0a	03	18	11	2e	27	3c	35	42	4b	50	59	66	6f	74	7d
	67	6a	7d	70	53	5e	49	44	0f	02	15	18	3b	36	21	2c
	b1	ba	a7	ac	9d	96	8b	80	e9	e2	ff	f4	c5	ce	d3	d8
e	37	39	2b	25	0f	01	13	1d	47	49	5b	55	7f	71	63	6d
	a1	a8	b3	ba	85	8c	97	9e	e9	e0	fb	f2	cd	c4	df	d6
	0c	01	16	1b	38	35	22	2f	64	69	7e	73	50	5d	4a	47
	7a	71	6c	67	56	5d	40	4b	22	29	34	3f	0e	05	18	13
f	d7	d9	cb	c5	ef	e1	f3	fd	a7	a9	bb	b5	9f	91	83	8d
	31	38	23	2a	15	1c	07	0e	79	70	6b	62	5d	54	4f	46
	dc	d1	c6	cb	e8	e5	f2	ff	b4	b9	ae	a3	80	8d	9a	97
	ca	c1	dc	d7	e6	ed	f0	fb	92	99	84	8f	be	b5	a8	a3

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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

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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

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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

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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

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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

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