Computer Security and Cryptography

CS381

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2016-03

Organization

- Week 1 to week 16 (2016-02-24 to 2016-06-08)
- 东上院502
- Monday 3-4节; week 9-16
- Wednesday 3-4节; week 1-16
- lecture 10 + exercise 40 + random tests 40 + other 10
- Ask questions **in** class – counted as points
- Turn ON your mobile phone (after lecture)
- Slides and papers:
  - http://202.120.38.185/CS381
    - **computer-security**
  - http://202.120.38.185/references
- TA: '薛伟佳' xue_wei_jia@163.com, '黄格仕' <huang.ge.shi@foxmail.com>
- Send homework to: laix@sjtu.edu.cn and to TAs

Rule: do not disturb others!

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Contents

- Introduction -- What is security?
- Cryptography
  - Classical ciphers
  - Today's ciphers
  - Public-key cryptography
  - Hash functions/MAC
  - Authentication protocols
- Applications
  - Digital certificates
  - Secure email
  - Internet security, e-banking

Network security
SSL
IPSEC
Firewall
VPN
Computer security
Access control
Malware
DDos
Intrusion
Examples
Bitcoin
Hardware
Wireless

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References

- W. Stallings, *Cryptography and network security - principles and practice*，Prentice Hall.
- W. Stallings, 密码学与网络安全：原理与实践（第4版），刘玉珍等译，电子工业出版社，2006
- Lidong Chen, Guang Gong, *Communication and System Security*, CRC Press, 2012.
- A.J. Menezes, P.C. van Oorschot and S.A. Vanstone, *Handbook of Applied Cryptography*. CRC Press, 1997, ISBN: 0-8493-8523-7, http://www.cacr.math.uwaterloo.ca/hac/index.html
- B. Schneier, *Applied cryptography*. John Wiley & Sons, 1995, 2nd edition.
- 裴定一,徐祥, 信息安全数学基础, ISBN 978-7-115-15662-4, 人民邮电出版社,2007.

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The IDEA cipher

- International Data Encryption Algorithm
- Block length 64-bit, key length 128-bit
- EU Project OASIS (88) (initial)
  - Key length of DES is too short (56 bits)
  - US export restrictions
  - Provable security (crypto is more art than science)
- Lai-Massy, Eurocrypt 90 (PES)
- Lai-Massey-Murphy, Eurocrypt 91 (IPES)
- Naming 92

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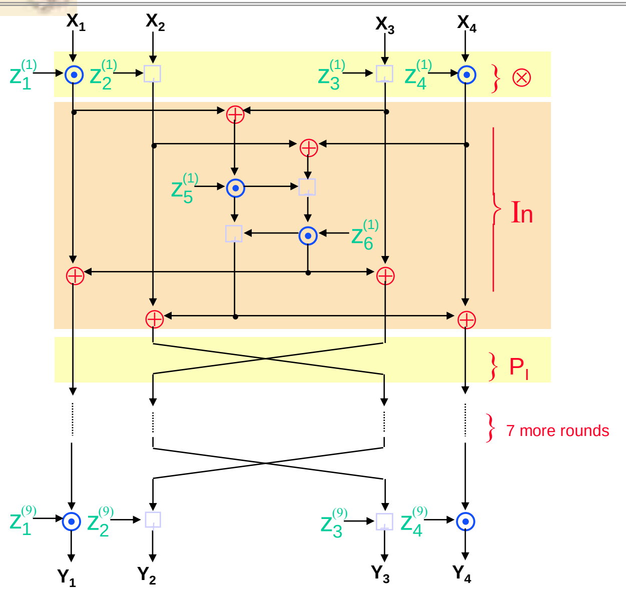
The IDEA cipher round function



$X_i, Y_j, Z_k^{(r)}$: 16-bit subblocks

⊕ : XOR of 16-bit strings

⊙ : multiplication mod $2^{16}+1$ of 16-bit integers with (0...0) ↔ 2^{16}

⊞ : addition mod 2^{16} of 16-bit integers

Eurocrypt'91, Lai, Massey & Murphy:
"Markov ciphers and differential cryptanalysis "

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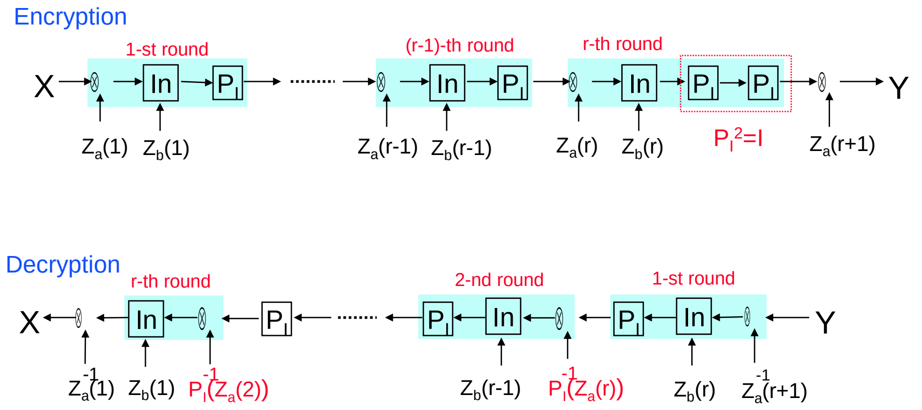
IDEA



P_I is a homomorphism of the group $(F_2^{64}, \otimes)$:
$P_I(\alpha\otimes\beta)=P_I(\alpha)\otimes P_I(\beta)$, $P_I(\alpha^{-1})=P_I(\alpha)^{-1}$

X⊗ Z=(x1⊙Z1, X2+Z2, X3+Z3,x4⊙Z4)

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Key schedule

128-bit key (16 blocks) $Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8$

Cyclic-shift to left by 25 bits $Z_9, Z_{10}, Z_{11}, Z_{12}, Z_{13}, Z_{14}, Z_{15}, Z_{16}$

....

$Z_{49}, Z_{50}, Z_{51}, Z_{52}$

Z_1	Z_2	Z_3	Z_4	Z_5	Z_6
Z_7	Z_8	Z_9	Z_{10}	Z_{11}	Z_{12}
Z_{13}	Z_{14}	Z_{15}	Z_{16}	Z_{17}	Z_{18}
Z_{19}	Z_{20}	Z_{21}	Z_{22}	Z_{23}	Z_{24}
Z_{25}	Z_{26}	Z_{27}	Z_{28}	Z_{29}	Z_{30}
Z_{31}	Z_{32}	Z_{33}	Z_{34}	Z_{35}	Z_{36}
Z_{37}	Z_{38}	Z_{39}	Z_{40}	Z_{41}	Z_{42}
Z_{43}	Z_{44}	Z_{45}	Z_{46}	Z_{47}	Z_{48}
Z_{49}	Z_{50}	Z_{51}	Z_{52}		

encryption

Z_{49}^{-1}	$-Z_{50}$	$-Z_{51}$	Z_{52}^{-1}	Z_{47}	Z_{48}
Z_{43}^{-1}	$-Z_{45}$	$-Z_{44}$	Z_{46}^{-1}	Z_{41}	Z_{42}
Z_{37}^{-1}	$-Z_{39}$	$-Z_{38}$	Z_{40}^{-1}	Z_{35}	Z_{36}
Z_{31}^{-1}	$-Z_{33}$	$-Z_{32}$	Z_{34}^{-1}	Z_{29}	Z_{30}
Z_{25}^{-1}	$-Z_{27}$	$-Z_{26}$	Z_{28}^{-1}	Z_{23}	Z_{24}
Z_{19}^{-1}	$-Z_{21}$	$-Z_{20}$	Z_{22}^{-1}	Z_{17}	Z_{18}
Z_{13}^{-1}	$-Z_{15}$	$-Z_{14}$	Z_{16}^{-1}	Z_{11}	Z_{12}
Z_7^{-1}	$-Z_9$	$-Z_8$	Z_{10}^{-1}	Z_5	Z_6
Z_1^{-1}	$-Z_2$	$-Z_3$	Z_4^{-1}		

decryption

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subkey bits

Dependency of subkey bits on the master key bits of IDEA.
i-th round

	$Z_1^{(i)}$	$Z_2^{(i)}$	$Z_3^{(i)}$	$Z_4^{(i)}$	$Z_5^{(i)}$	$Z_6^{(i)}$
1	0–15	16–31	32–47	48–63	64–79	80–95
2	96–111	112–127	25–40	41–56	57–72	73–88
3	89–104	105–120	121–8	9–24	50–65	66--81
4	82–97	98–113	114–1	2–17	18–33	34–49
5	75–90	91–106	107–122	123–10	11–26	27–42
6	43–58	59–74	100–115	116–3	4–19	20–35
7	36–51	52–67	68–83	84–99	125–12	13–28
8	29–44	45–60	61–76	77–92	93–108	109–124
O	22–37	38–53	54–69	70–85		

Group operations

- Design basis: mixing different group operations.
- For both confusion and diffusion
- Having "one-time-pad" security
- Object: n-bit blocks (n=8, 16, 32)
- Available: XOR, Add mod 2^n,
- Integer multiplication: available for most CPU, require Z_p^*, P prime.
- Multiplication mod 2^n+1 is invertible if n=1,2,4,8,16 (Fermat primes)
- It is unknown if other Fermat prime exists
- IDEA can have block size of 4, 8, 16, 32, 64 bits (unfortunately not 128).

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multiplication

- Example n=2, $Z_5^*=\{1,2,3,4\} \leftrightarrow \{1,2,3,0\}=F_2^2$
- { (00),(01),(10),(11) } ↔ { 4, 1, 2, 3}, 4=100
- 2⊙3=1, 2⊙2=0

  0⊙2=(4×2 mod 5)=(-1×2 mod 5)=3

⊙	0	1	2	3
0	1	0	3	2
1	0	1	2	3
2	3	2	0	1
3	2	3	1	0

Efficient computation of ⊙

For n=16, directly compute ab mod 65537 is expensive (division).

Low-high algorithm

- ab mod 2^n+1 =

  (ab mod 2^n) –(ab div 2^n) if (ab mod 2^n) ≥ (ab div 2^n)

  (ab mod 2^n) –(ab div 2^n) $+2^n+1$ if (ab mod 2^n) < (ab div 2^n)
- where ab div 2^n is the quotient when ab is divided by 2^n
  - ab mod 2^n corresponds to the lower n bits of ab
  - ab div 2^n is the higher n bits of ab
- Because ab = $q(2^n+1)+r = q2^n + (q+r) = (q+1)2^n + (q+r-2^n)$

  $q+r<2^n$ $\quad$ $q+r \geq 2^n$
- Example: 4·8 mod 17= (32 mod 17)=(0010,0000) mod 17)

  =(32 mod 16)–(32 div 16) + 17 = (0000)–(0010)+17=15

Exp and log table look-up: $x \cdot y = g^{\log(x)+\log(y)}$

For n=16, size of table is 2·65536 bytes

properties

- 3 group operations on 16-bit blocks
- Incompatible: non-associative, non-distributive
- Non-isotopic:
  - Isotopic: exist f,g,h, s.t., f(a*b)=g(a)#h(b)
- Confusion
  - Interaction of 3 operations
  - Consecutive operations are different
- Diffusion
  - MA structure, In
  - Complete in 1 round (each input-bit influences every output bit)

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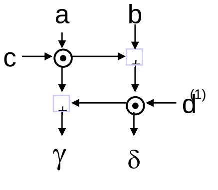
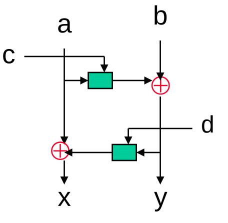
MA and In

MA structure

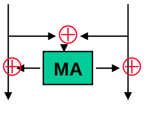




2 round Feistel

MA structure uses the least number of operations (4) to achieve ‘complete diffusion’ – each out put depends on every input

Involution In: In^2=identity



In

•In can be viewed as 2 round Feistel structure
•Thus, 1 round of IDEA is more than 2 rounds Feistel
•IDEA has 8.5 rounds

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Known attacks

Attacks on reduced IDEA (total 8.5 rounds)

rounds	data	process	(memory)	attacks
2.5	2^{10}	2^{106}		differential (Meier 92)
2.5	2	2^{37}		square (Nakahara-Barreto-Preneel 02)
3	2^{22}	2^{50}		linear (Junod, FSE05)
3.5	2^{56}	2^{67}		truncated diff.(Borst-Knudsen-Rijmen 97)
3.5	103	2^{97}		linear (Junod, FSE05)
4	2^{37}	2^{70}		impossible (Biham-Birykov-Shamir 99)
4.5	2^{64}	2^{112}		impossible differential (Alix-Biham-Shamir 98)
4.5	2^{24}	2^{121}	(2^{64})	collision (Demirci-Ture-Selcuk, SAC03)
5	2^{24}	2^{126}	(2^{64})	collision (Demirci-Ture-Selcuk, SAC03)
5	2^{19}	2^{103}		Biham-Dunkelman-Keller, AC06
6	2^{49}	2^{112}		differential-linear (Sun-Lai, AC09)
6	2	$2^{123.4}$		Meet-in-the-Middle (Keller,Biham,,C11)
8.5	2^{52}	$2^{126.06}$		biclique(Khovratovich-Lurent-Rechberg,EC12)
Max	2^{64}	2^{127}		

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Other issues

- No S-box, so nothing to hide
- Weak-keys:
  - Special value ‘0 (-1)’ and ‘1’ have less confusion and diffusion effect: $0 \boxplus x=x$, $0 \otimes x=-x$, $1 \otimes x=x$
  - Linear key schedule
  - Sets of weak keys of size about 2^{51} [Daemen 94], 2^{63} [Hawks 98], 2^{63} [Biryukov 02]
  - Simple fix: XOR a constant to subkeys
- Obtain non-standard but stronger version of IDEA.
- 128-bit version: MESH, IDEA-NXT, new ones?

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Exercise 5.

1. prove the low-high algorithm for computing ⊙
2. prove that the In-structure in IDEA is an involution.

Deadline: before next lecture

AES – Advanced Encryption Standard

- Block cipher, 128-bit block; 128,194,256-bit key
- Fast for SW and 8-bit processor
- More secure and faster than DES?
- 1997-04: requirements (128-bit?,free?,..)
- 1997-10: NIST 1-st call
- 1998-08: 1-st AES Conference, Ventura, USA
  - 15 accepted submissions
- 1999-03: 2-nd AES Conference, Rome
- 1999-8: five final candidates
- 2000-03: 3-rd AES Conference, New York
- 2000-10-02: decision -- Rijndael
- 2001-11: published as FIPS PUB 197

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AES candidates

- **CAST-256** Entrust Tech. (rep. Carlisle Adams)
- **CRYPTON** Future Systems, Inc. (rep Chae Hoon Lim)
- **DEAL** Richard Outerbridge, Lars Knudsen (attack 2^{70})
- **DFC** CNRS - Ecole Normale Superieure (rep Serge Vaudenay)
- **E2** NTT - (represented by Masayuki Kanda)
- **FROG** TecApro Int. S.A. (rep Dianelos Georgoudis) - attack (2^{56})
- **HPC** Rich Schroeppel (???)
- **LOKI97** Lawrie Brown, Josef Pieprzyk, Jennifer Seberry -Attacks known (2^{56})
- **MAGENTA** Deutsche Telekom (Klaus Huber) broken: trivial chosen plaintext; other 2^{56}
- **MARS** IBM (represented by Nevenko Zunic) some weakness
- **RC6** RSA Laboratories (rep Matthew Robshaw)
- **RIJNDAEL** **Joan Daemen, Vincent Rijmen**
- **SAFER+** Cylink Corporation (rep Lily Chen)
- **SERPENT** Ross Anderson, Eli Biham, Lars Knudsen
- **TWOFISH** B. Schneier, J. Kelsey, D. Whiting, D. Wagner, C. Hall, N. Ferguson

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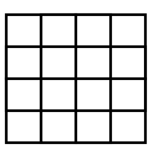
AES parameters

- Number of rounds 10 /12 /14
- Keysize: 128/192/256 bit keys

Unit: 32-bit words

	Key Length (Nk words)	Block Size (Nb words)	Number of Rounds (Nr)
AES-128	4	4	10
AES-192	6	4	12
AES-256	8	4	14

- Text: 128-bit data, represented as 4 by 4 matrix of 8-bit bytes.



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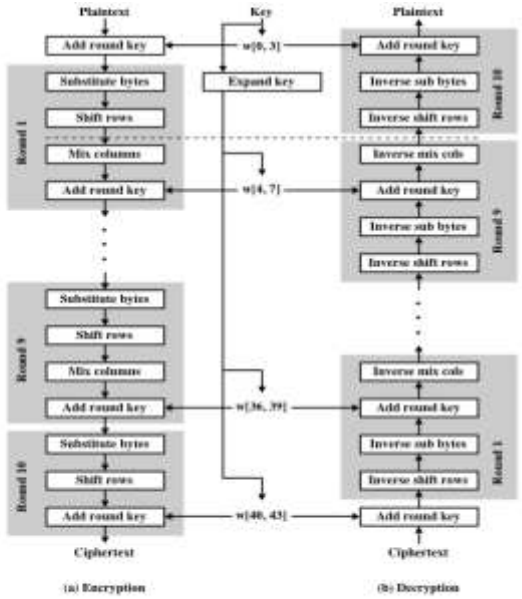
AES Encryption and Decryption

- Add key
- S-box
- Shift row
- Mix column
- Add key-0
- S-box
- Shift row
- Mix column
- Add key-1
- .
- .
- S-box
- Shift row
- Add key-last



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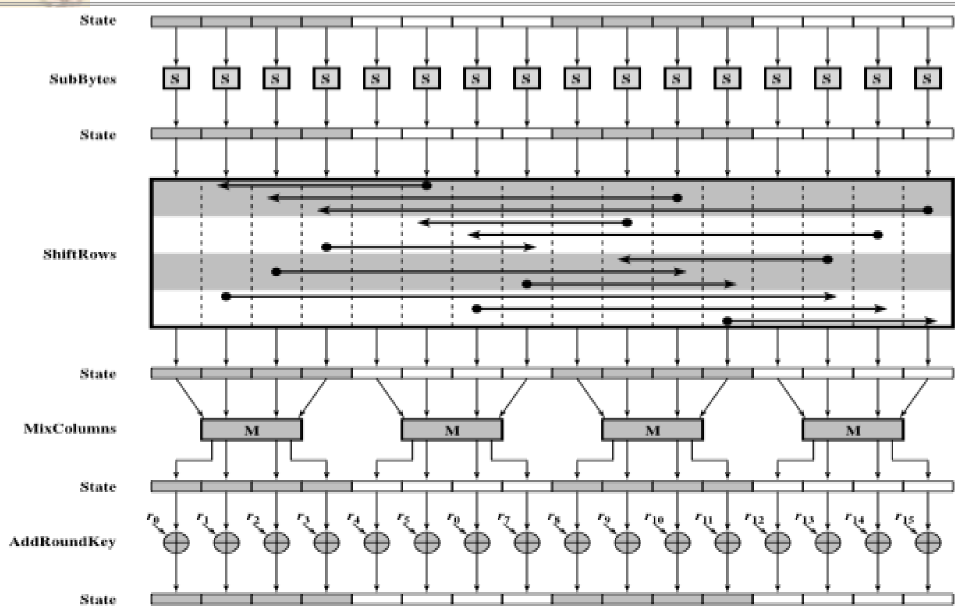
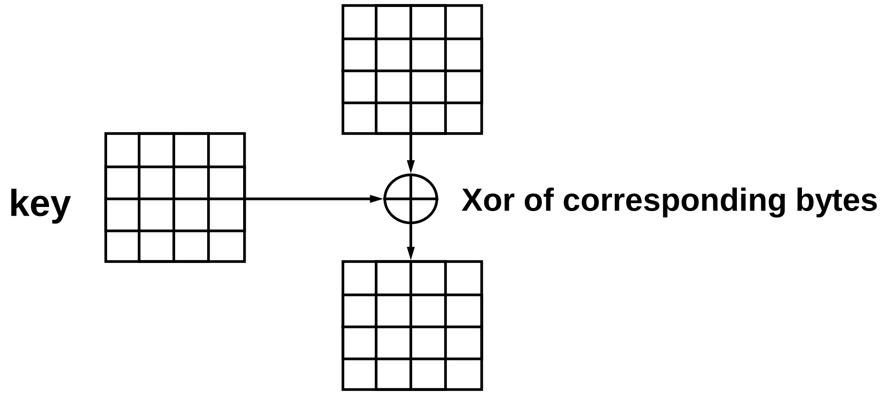
AES Round



Add key operation



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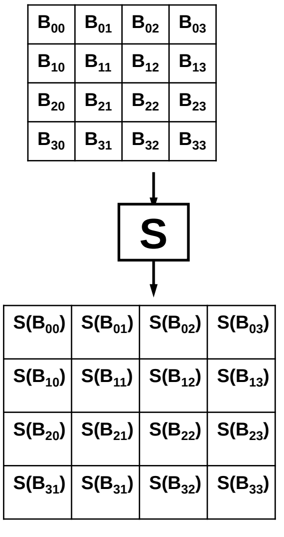
S-box



- **8-bit lookup table**
- **16 lookups in parallel**

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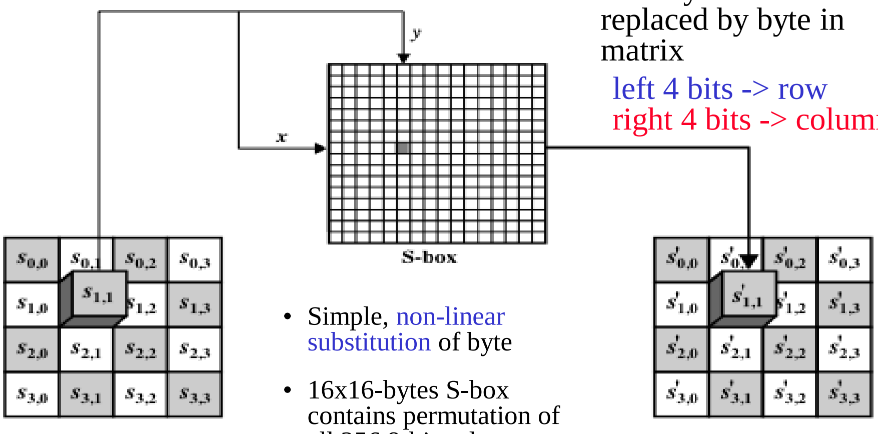
Use of S-box

- each byte of state is replaced by byte in matrix

  left 4 bits -> row
  right 4 bits -> column



- Simple, non-linear substitution of byte
- 16x16-bytes S-box contains permutation of all 256 8-bit values

Substitution: two-dimensional table look-up

S-box

S(*x*,*y*)

x \ *y*	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	01	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	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
5	53	D1	00	ED	20	FC	B1	5B	6A	CB	BE	39	4A	4C	58	CF
6	D0	EF	AA	FB	43	4D	33	85	45	F9	02	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	06	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	08
C	BA	78	25	2E	1C	A6	B4	C6	E8	DD	74	1F	4B	BD	8B	8A
D	70	3E	B5	66	48	03	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

byte {95} is replaced by row 9, column 5 (is {2A})

Inverse S-box

		y															
		0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
x	0	52	09	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	08	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	00	8C	BC	D3	0A	F7	E4	58	05	B8	B3	45	06
	7	D0	2C	1E	8F	CA	3F	0F	02	C1	AF	BD	03	01	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	07	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	04	7E	BA	77	D6	26	E1	69	14	63	55	21	0C	7D

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Rationale for S-box Design

- low correlation between input and output bits
- output is no simple function of input
- S-box has no fixed points, i.e., S(a) ≠ a
- S-box is not self-inverse, i.e., S(a) ≠ InvS(a)
- The mapping $x \to x^{-1}$ has high non-linear degree and good differential distribution.

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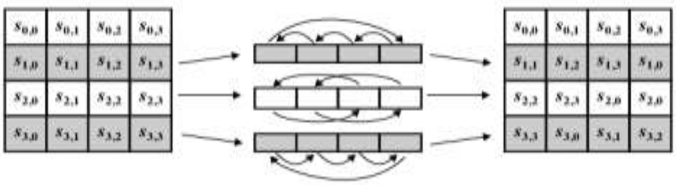
Shift Row Transformation

- a circular byte shift in each each
  - 1^{st} row is unchanged
  - 2^{nd} row does 1 byte circular shift to left
  - 3rd row does 2 byte circular shift to left
  - 4th row does 3 byte circular shift to left
- decrypt does shifts to right
- this step permutes bytes between the columns



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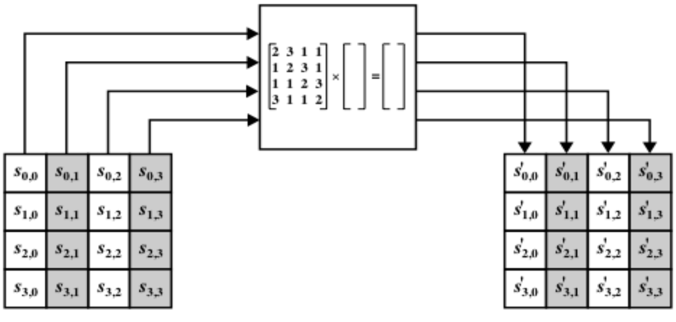
Mix Column Transformation



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MDS matrix

- A 4×4 matrix over GF(2^8).
- Matrix is an MDS (Maximum Distance Separable).
- Byte-Hamming weight of input + output is at least 5.

Input weight	Output weight
1	4
2	>= 3
3	>= 2
4	>= 1

•High diffusion – effective against differential and linear attacks

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Inverse Mix Column Transformation

- just like Mix Column Transformation
- however, each column is multiplied modulo x^4+1 with fixed polynomial $'0B'x^3 + '0D'x^2 + '09'x + '0E'$
- same as:

$$\begin{bmatrix} s'_{0,0} & s'_{0,1} & s'_{0,2} & s'_{0,3} \\ s'_{1,0} & s'_{1,1} & s'_{1,2} & s'_{1,3} \\ s'_{2,0} & s'_{2,1} & s'_{2,2} & s'_{2,3} \\ s'_{3,0} & s'_{3,1} & s'_{3,2} & s'_{3,3} \end{bmatrix} = \begin{bmatrix} 0E & 0B & 0D & 09 \\ 09 & 0E & 0B & 0D \\ 0D & 09 & 0E & 0B \\ 0B & 0D & 09 & 0E \end{bmatrix} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix}$$

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AES Key Expansion

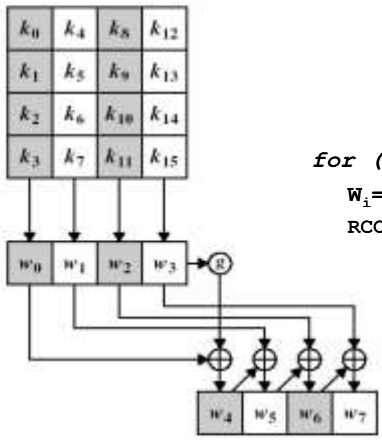

Figure 5.6 AES Key Expansion

128bit =4word Key ⇒ 4*11word subkey
192bit=6word Key ⇒ 4*13word subkey
256bit=8word Key ⇒ 4*15word subkey

for (i mod 4)=0

$W_i = W_{i-4} \oplus Sub(RotWord(W_{i-1})) \oplus RCON(i)$

$RCON(i) = 2^{(i-4)/4} = 1,2,4,8$......

RCON

01	02	04	08	10	20	40	80	1b	36
00	00	00	00	00	00	00	00	00	00
00	00	00	00	00	00	00	00	00	00
00	00	00	00	00	00	00	00	00	00

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AES Decryption

Decryption process is different from encryption process
- Inverse S-box.
- Inverse of MDS matrix.
- Modified round keys, or modified operation order.
- Requires extra hardware.

Decryption key
- Cannot directly generate round keys in reverse order.
- Decryption must either store all round keys, or pre-compute the 'final' state and work backwards from that.
- Requires extra time from getting key to start of first decryption.

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Implementation

- on 8-bit CPU
  - byte substitution works on bytes using a table of 256 entries
  - shift rows is simple byte shifting
  - add round key works on byte XORs
  - mix columns requires matrix multiply in $GF(2^8)$ which works on byte values, can be simplified to use a table lookup
- on 32-bit CPU
  - redefine steps to use 32-bit words
  - can pre-compute 4 tables of 256-words
  - each column in each round can be computed using 4 table lookups + 4 XORs
  - at a cost of 16Kb to store tables
- designers believe this efficient implementation was a key factor in its selection as the AES cipher
- Round function is embedded in new Intel CPU

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Security

- Impossible Differential attack on 7-round: 2^{112}, 2^{112}, 2^{117}
- Related-key attack on full AES [AC09].
- BiClique Attacks on full AES: complexity 2^{k-1.3}, for k=128, 192, 256. [AC 2011]
- Algebraic structures: BES, extended to a larger space $GF(2^8)$, easy to analyze. [Murphy-Robshaw, Crypto02]
- Algebraic attacks [Courteous-Pieprzyk, AC02]: written as an over-defined system of multivariate quadratic equations (MQ), solvable using XSL[Shamir, EC00];
  - claimed to be able to attack BES in about 2^{87} or 2^{100} operations??
  - Algebraic attacks may not work as expected [Cid-Leurent, AC05]
- Linearity and slow diffusion in key schedule

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