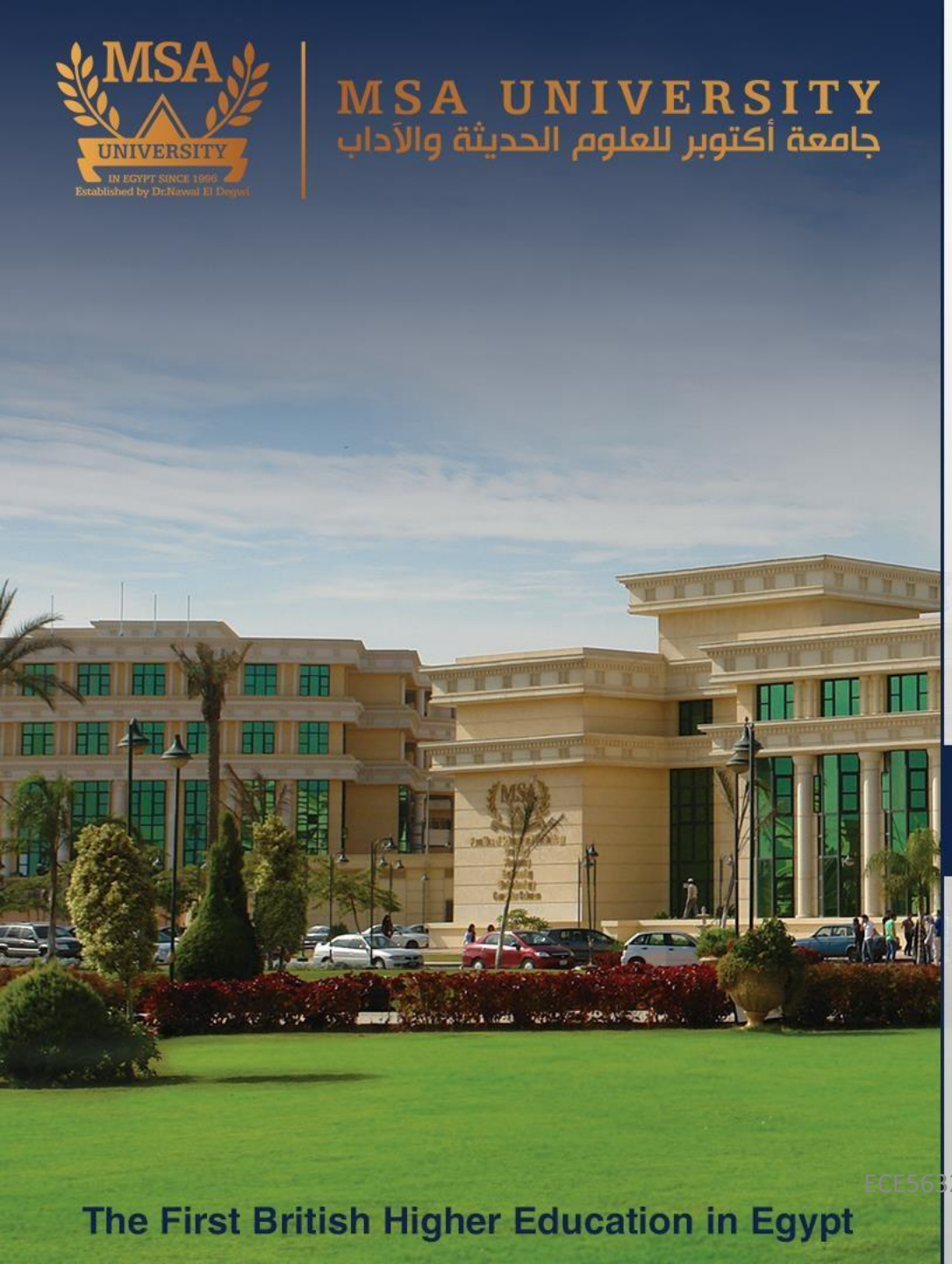


Cryptography
ECE5632 - Spring 2026

Lecture 6B

Dr. Farah Raad

Lecture Topic

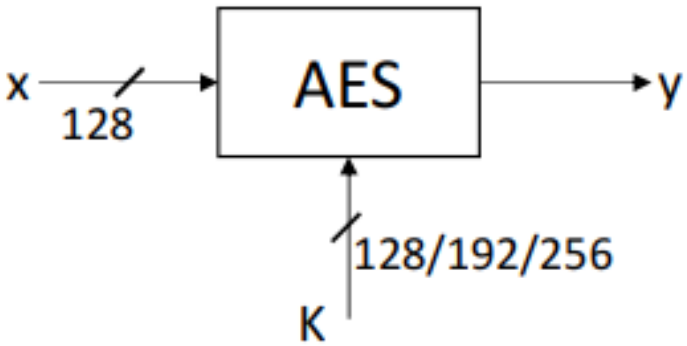
The Advanced Encryption Standard (AES)

The Advanced Encryption Standard (AES)

- AES is the most widely used symmetric cipher today.
- Found in every web browser, in banking machines, WiFi routers, etc ..

❖ The requirements for all AES candidate submissions were:

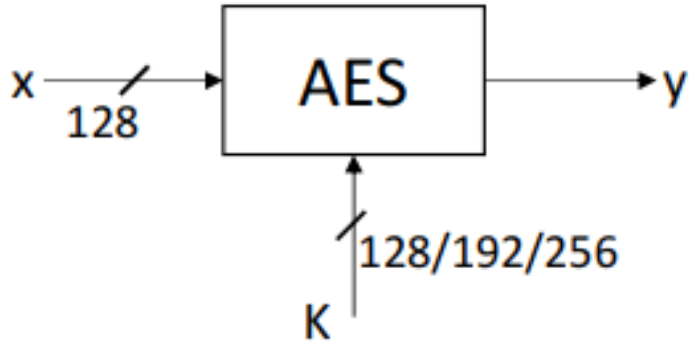
- Block cipher with **128-bit block size**
- **Three supported key lengths**: 128, 192 and 256 bit
- Security relative to other submitted algorithms
- **Efficiency** in software and hardware



The Advanced Encryption Standard (AES)

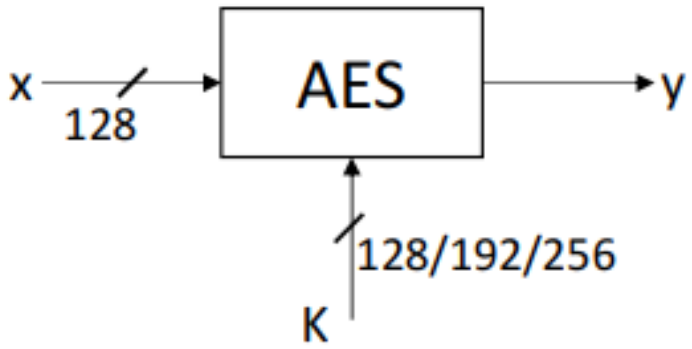
- **The number of rounds depends on the chosen key length:**

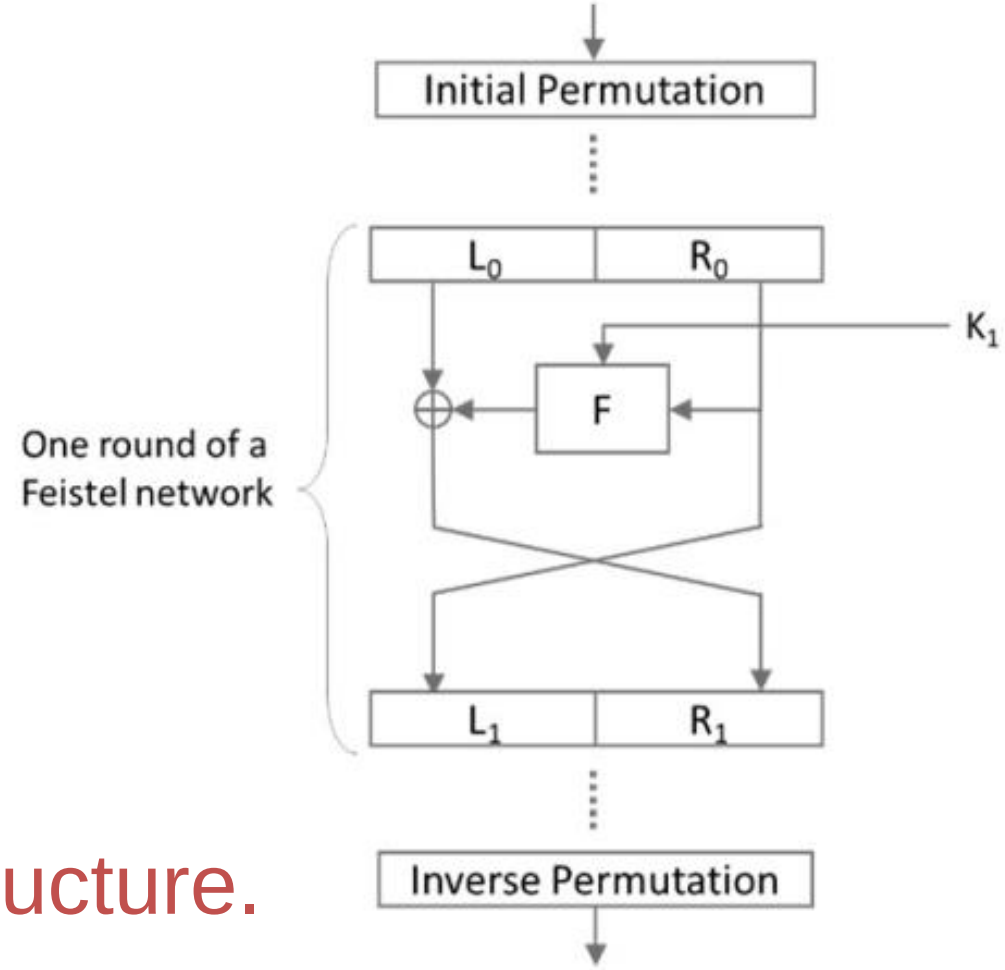
Key length (bits)	Number of rounds
128	10
192	12
256	14



Structure of AES

✓ Remember the Feistel structure? (e.g., SDES, DES)



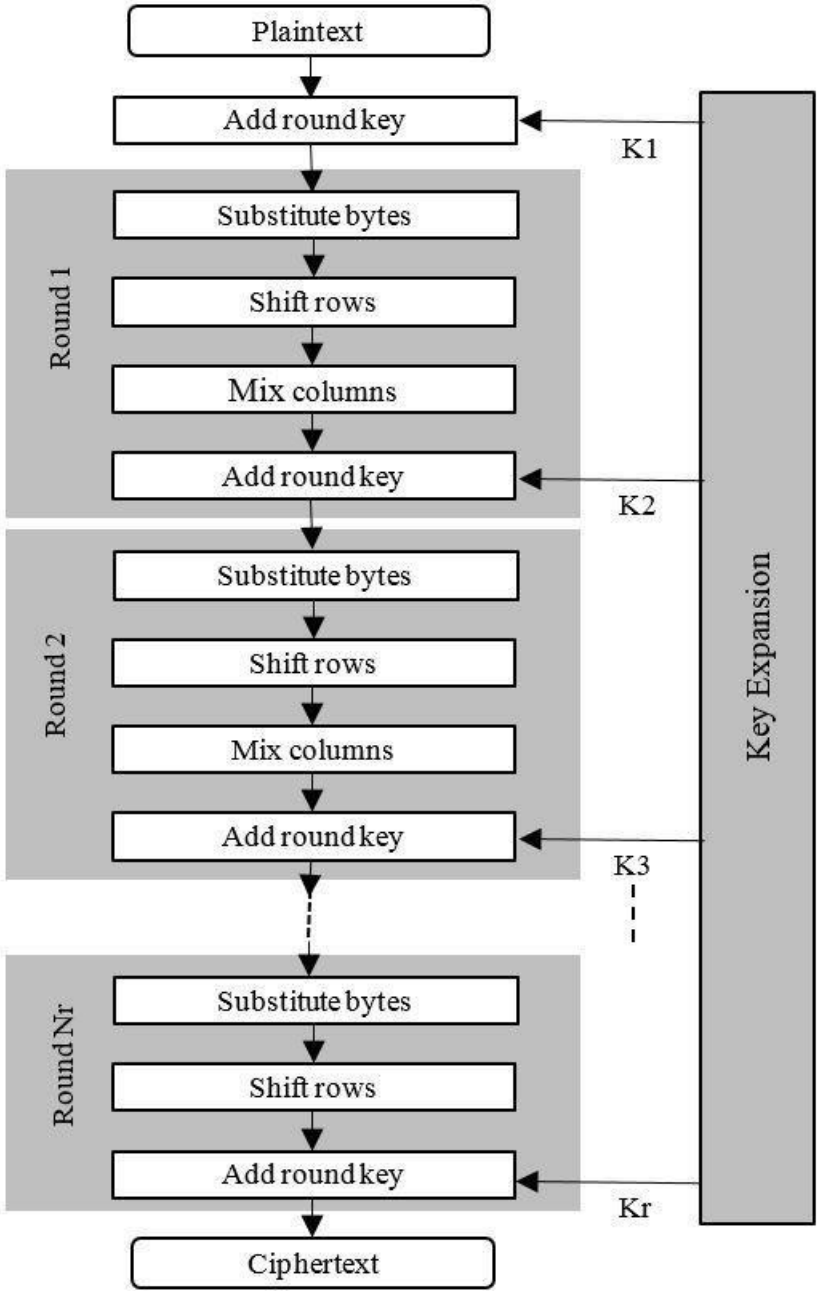


AES does **NOT** use the Feistel structure.

Structure of AES

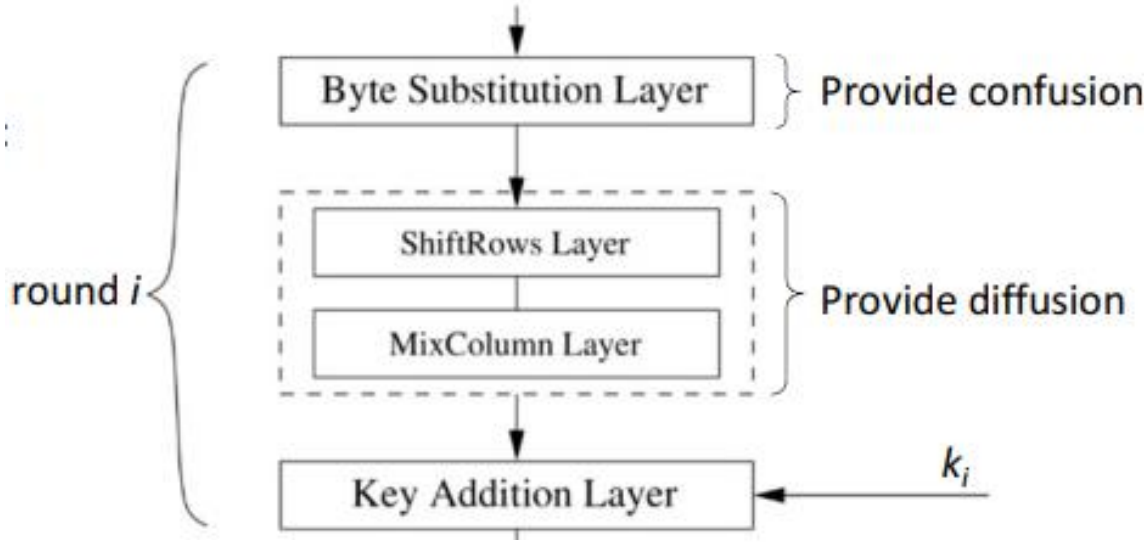
- AES encrypts all 128 bits of the data path in each round.
- A subkey is added at the beginning and at the end of encryption (**key whitening**)
- AES number of rounds depend on the key length:

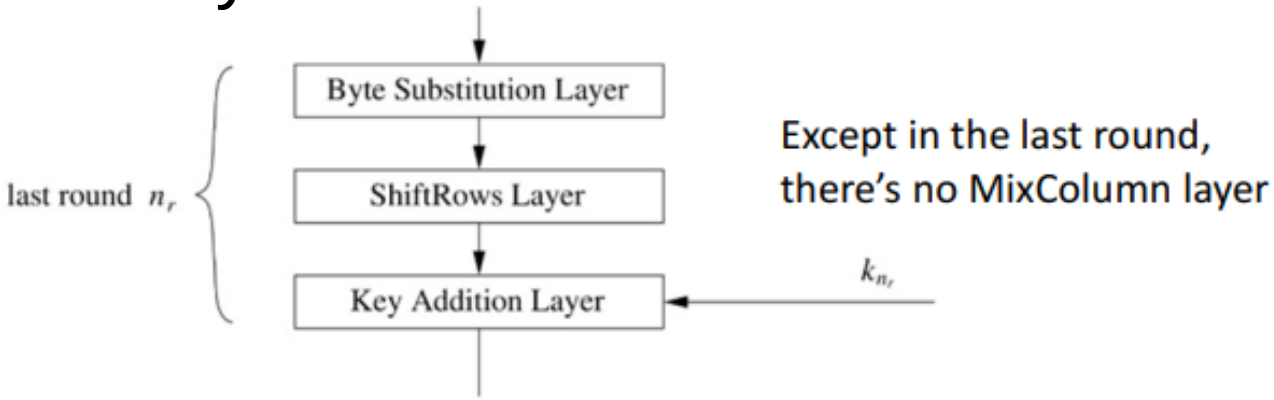
key length	# rounds = n_r
128 bit	10
192 bit	12
256 bit	14



Structure of AES

- Each round consists of 4 layers:
  1) Byte Subsitution
  2) Shift Row
  3) Mix Column
  4) Key Addition
- Except in the last round, there's no Mix Column layer





Structure of AES

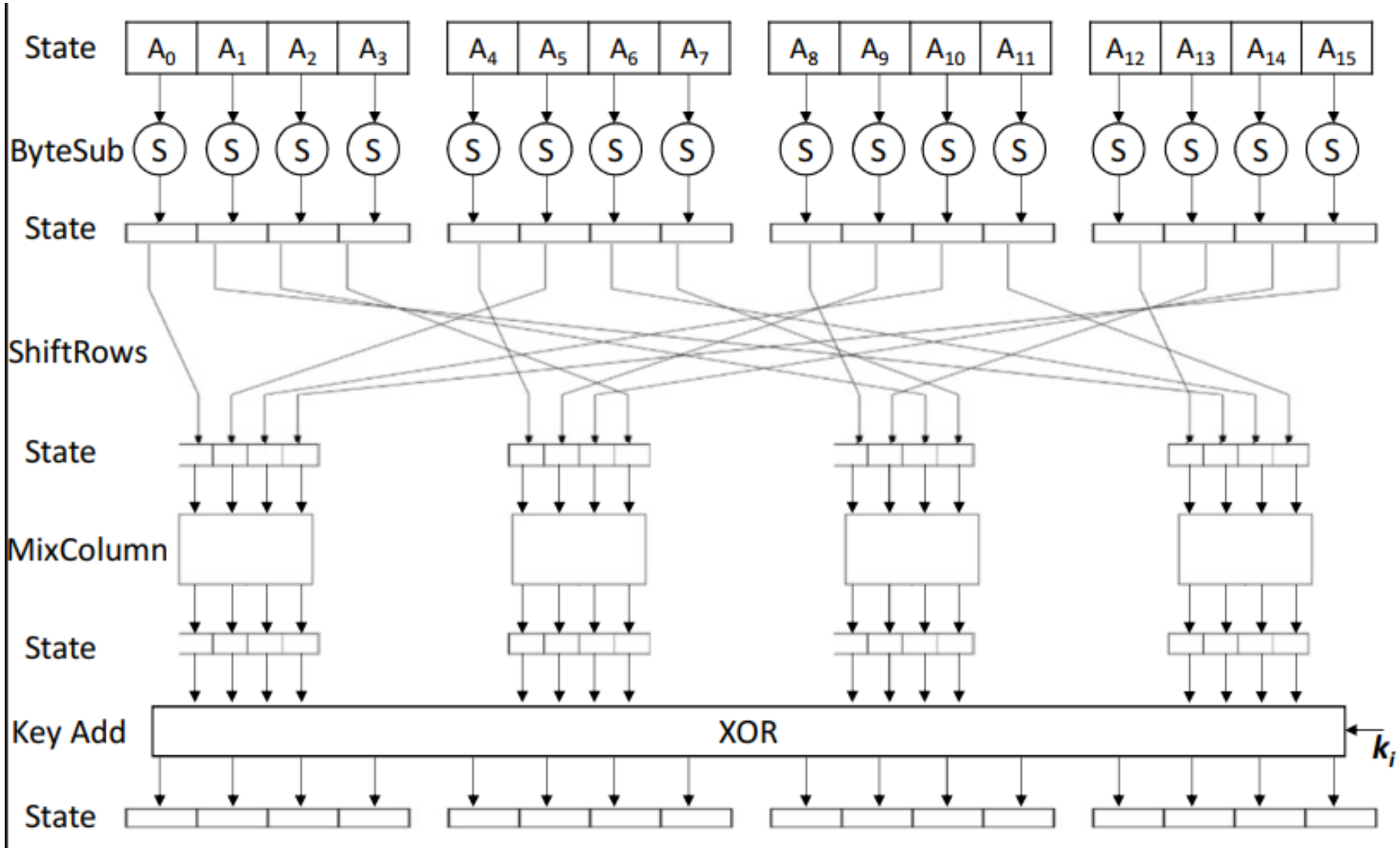
- **Note:** AES is byte oriented cipher.
- The 128 bit data block (data path) is split into 16 bytes.
- with A0,…, A15 denoting the 16-byte input of AES

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}

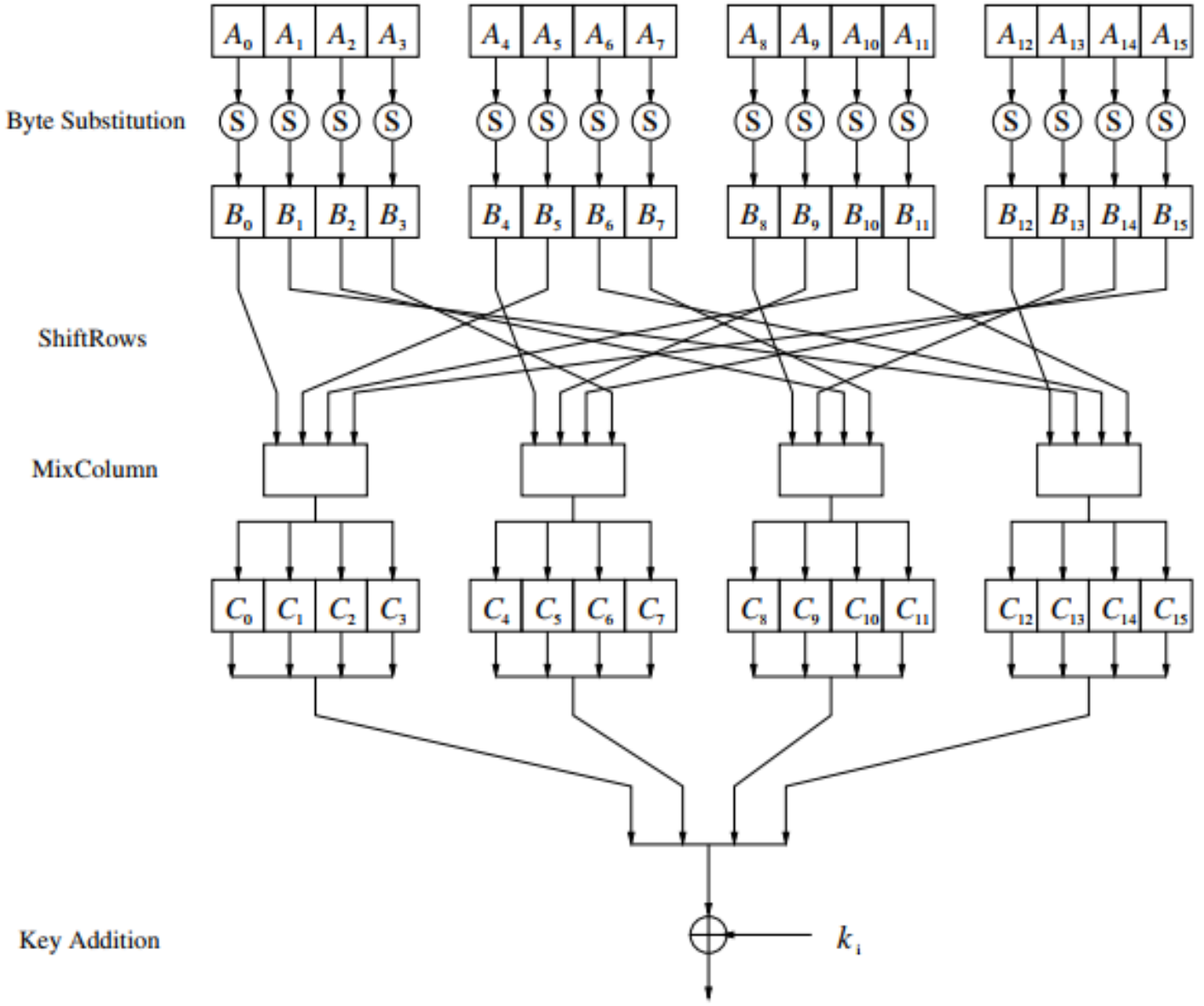
Bytes $A_0, A_1, \ldots, A_{15}$ are arranged in a four-by-four byte matrix called the state.

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}

AES Encryption Round



AES Encryption Round



AES Internals

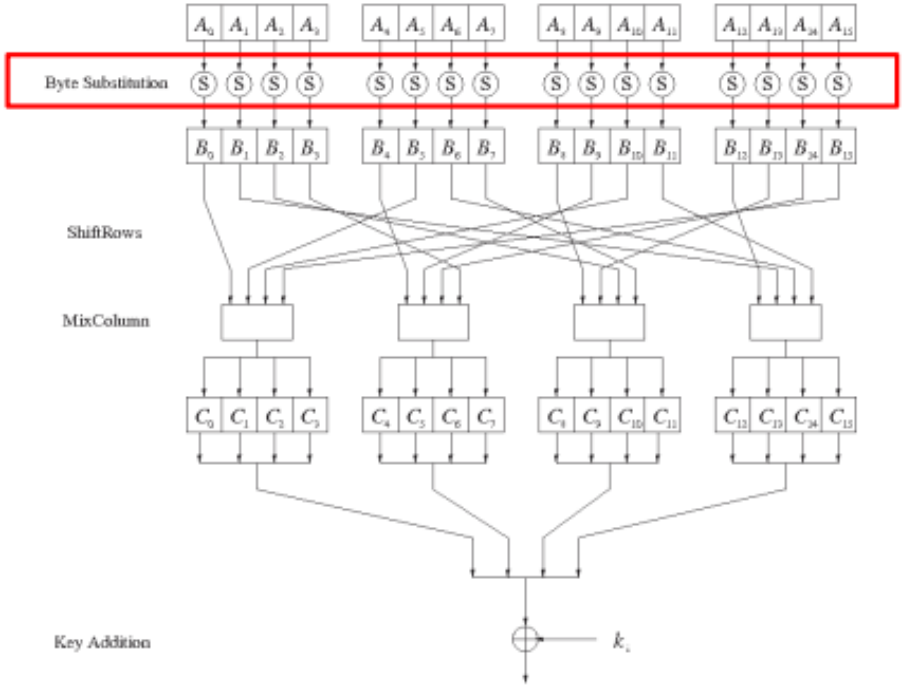
a) The Byte Substitution Layer:

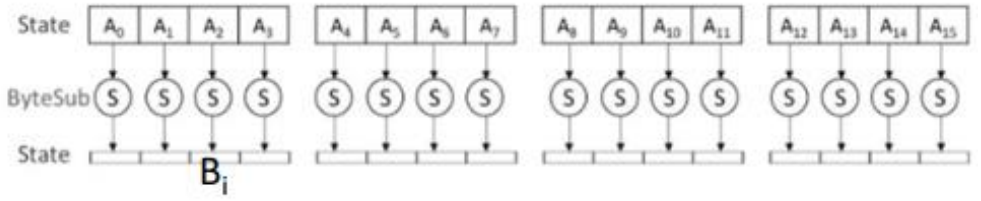
- The Byte Substitution layer consists of 16 **S-Boxes** with the following properties:

  The S-Boxes are

  - **identical**
  - the only **nonlinear** elements of AES, i.e., ByteSub(A_i) + ByteSub(A_j) ≠ ByteSub(A_i + A_j), for i,j = 0,…,15
  - **bijective**, i.e., there exists a one-to-one mapping of input and output bytes

    ⇒ S-Box can be uniquely reversed

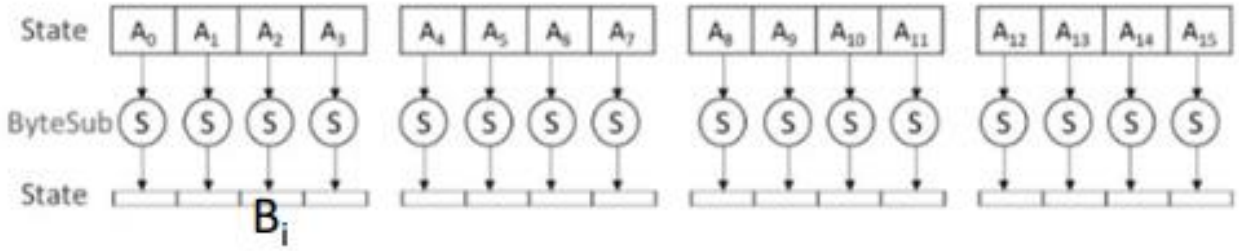




- In software implementations, the S-Box is usually realized as a lookup table

AES Internals

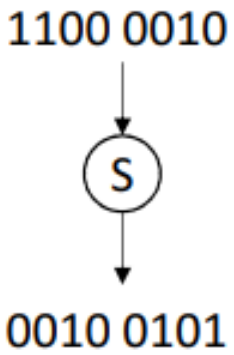
a) The Byte Substitution Layer:



Example

$A_i = C2_{16} = (xy)$

$B_i = S(A_i) = 25_{16}$



AES S-Box: Substitution values in hexadecimal notation for input byte (xy)

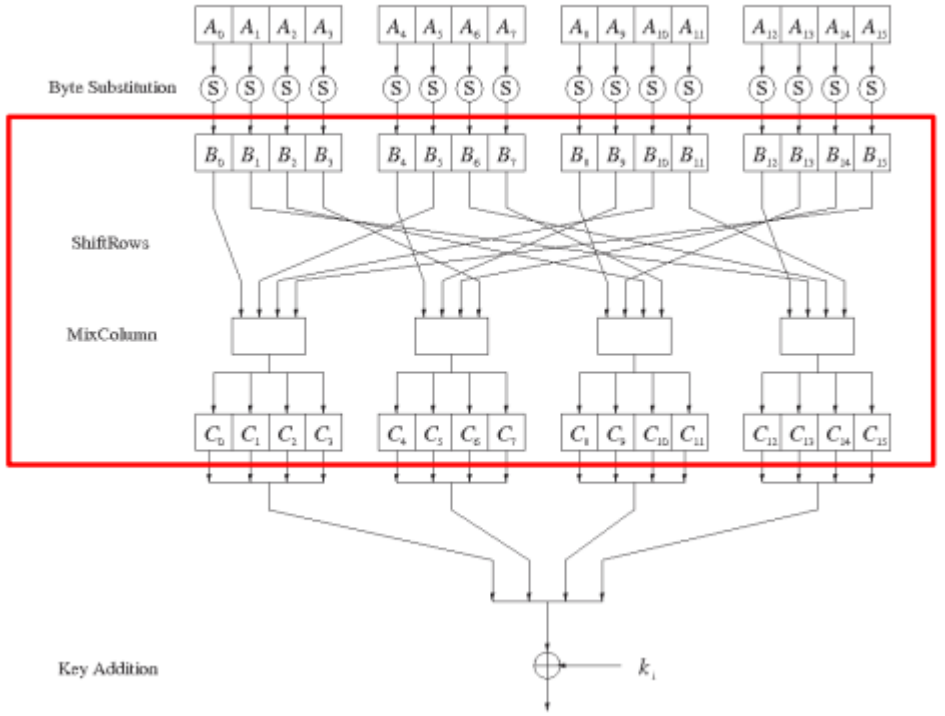
x \ y	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	63	7C	77	7B	F2	6B	6F	C5	30	01	67	2B	FE	D7	AB	76
1	CA	82	C9	7D	FA	59	47	F0	AD	D4	A2	AF	9C	A4	72	C0
2	B7	FD	93	26	36	3F	F7	CC	34	A5	E5	F1	71	D8	31	15
3	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
5	53	D1	00	ED	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

AES Internals (Diffusion Layer)

b) The Diffusion layerr:

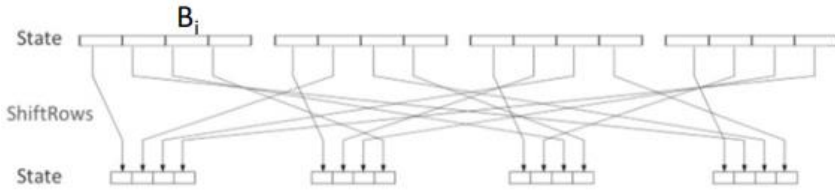
- provides diffusion over all input state bits
- consists of two sublayers:
  - **ShiftRows Sublayer**: Permutation of the data on a byte level
  - **MixColumn Sublayer**: Matrix operation which combines ("mixes") blocks of four bytes
- performs a linear operation on state matrices *A*, *B*, i.e.,

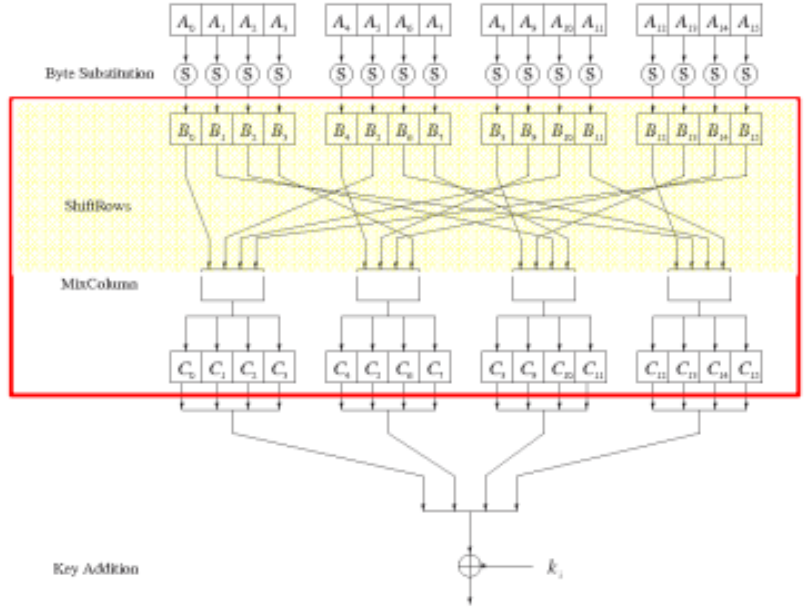
$$\text{DIFF}(A) + \text{DIFF}(B) = \text{DIFF}(A + B)$$



AES Internals (Diffusion Layer)

1) Shift Rows Sublayer:





Outputs of 16 S-Boxes are rolled in a 4x4 state matrix:

B_0	B_4	B_8	B_{12}
B_1	B_5	B_9	B_{13}
B_2	B_6	B_{10}	B_{14}
B_3	B_7	B_{11}	B_{15}

After the Shift Rows operation, the new state matrix becomes as follows:

B_0	B_4	B_8	B_{12}	no shift
B_5	B_9	B_{13}	B_1	⟵ one position left shift
B_{10}	B_{14}	B_2	B_6	⟵ two positions left shift
B_{15}	B_3	B_7	B_{11}	⟵ three positions left shift

So, the input to the next layer becomes:

B_0	B_5	B_{10}	B_{15}	B_4	B_9	B_{14}	B_3	B_8	B_{13}	B_2	B_7	B_{12}	B_1	B_6	B_{11}

Input matrix

B_0	B_4	B_8	B_{12}
B_1	B_5	B_9	B_{13}
B_2	B_6	B_{10}	B_{14}
B_3	B_7	B_{11}	B_{15}

Output matrix

B_0	B_4	B_8	B_{12}
B_5	B_9	B_{13}	B_1
B_{10}	B_{14}	B_2	B_6
B_{15}	B_3	B_7	B_{11}

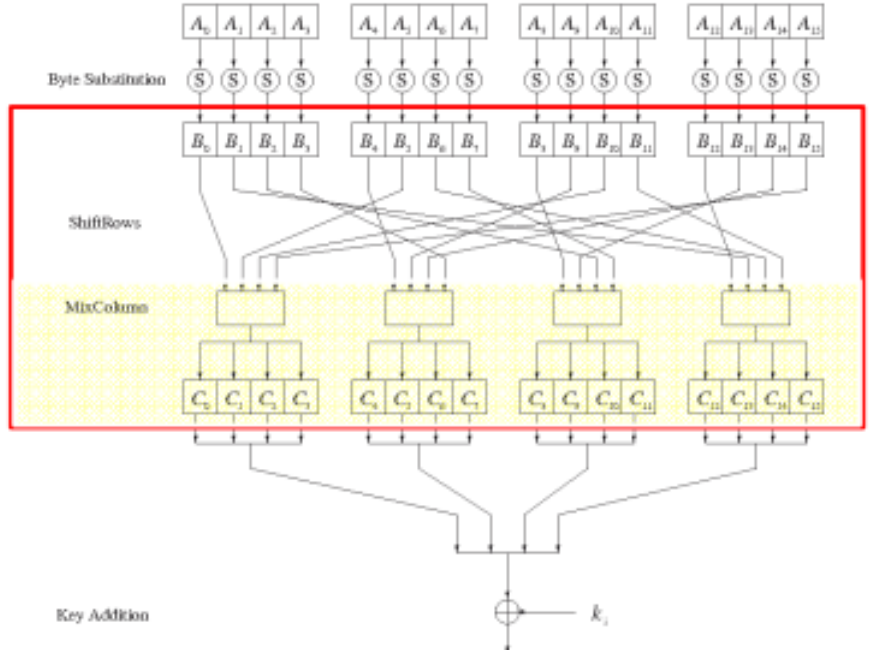
AES Internals (Diffusion Layer)

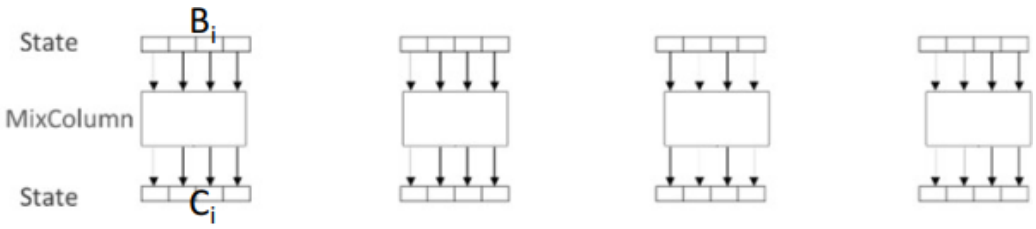
2. MixColumn Sublayer

- Each 4-byte column is considered as a vector and multiplied by a fixed 4x4 matrix, e.g.,

$$\begin{pmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{pmatrix} = \begin{pmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{pmatrix} \cdot \begin{pmatrix} B_0 \\ B_5 \\ B_{10} \\ B_{15} \end{pmatrix}$$

where 01, 02 and 03 are given in hexadecimal notation



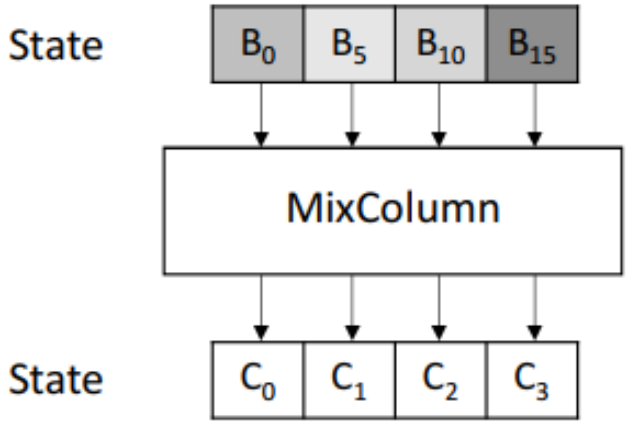


AES Internals (Diffusion Layer)

2. MixColumn Sublayer

Example:

1st MixColumn Box (other three are identical)



$$\begin{pmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{pmatrix} = \begin{pmatrix} 02\ 03\ 01\ 01 \\ 01\ 02\ 03\ 01 \\ 01\ 01\ 02\ 03 \\ 03\ 01\ 01\ 02 \end{pmatrix} \begin{pmatrix} B_0 \\ B_5 \\ B_{10} \\ B_{15} \end{pmatrix}$$

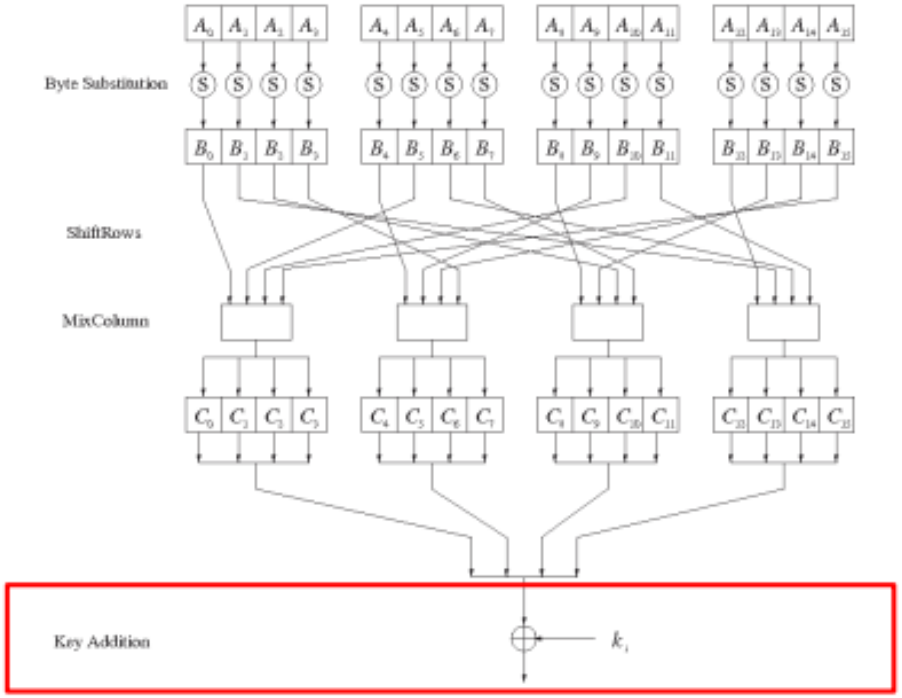
This way, 1 bit flip in any of the input bytes affects C_0, C_1, C_2, C_3.

Note: The multiplications and additions for each C_i is done in $GF(2^8)$ with $P(x) = x^8 + x^4 + x^3 + x + 1$

AES Internals

C. Key Addition Layer

- Inputs:
  - 16-byte state matrix C
  - 16-byte subkey k_i
- Output: $C \oplus k_i$
- The subkeys are generated in the key schedule



Key Schedule

- Subkeys are derived recursively from the original 128/192/256-bit input key
- Each round has 1 subkey, plus 1 subkey at the beginning of AES

key length	# rounds = n_r
128 bit	10
192 bit	12
256 bit	14

Key length (bits)	Number of subkeys
128	11
192	13
256	15

- Key whitening: Subkey is used both at the input and output of AES
  $\Rightarrow$ # subkeys = # rounds + 1
- There are different key schedules for the different key sizes

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Thank You!

See You next Lectures!!
Any Question?

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