PESU ISFCR

PESU Center for
Information Security,
Forensics and
Cyber Resilience

PES UNIVERSITY

Welcome to

PES University

Ring Road Campus, Bengaluru

APPLIED CRYPTOGRAPHY

Lecture 10

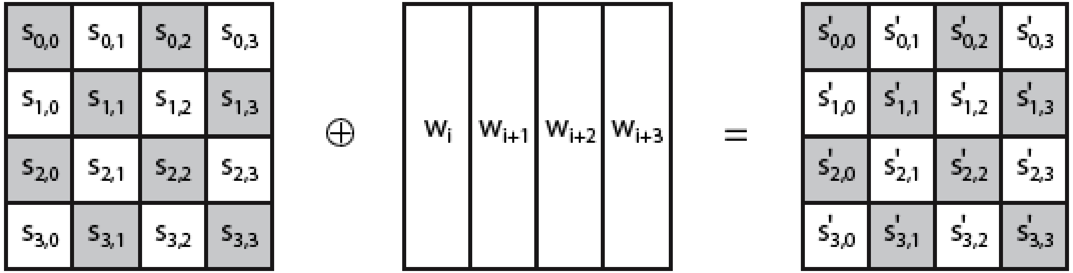
AES key scheduling

Subkey generation

AddRoundKey

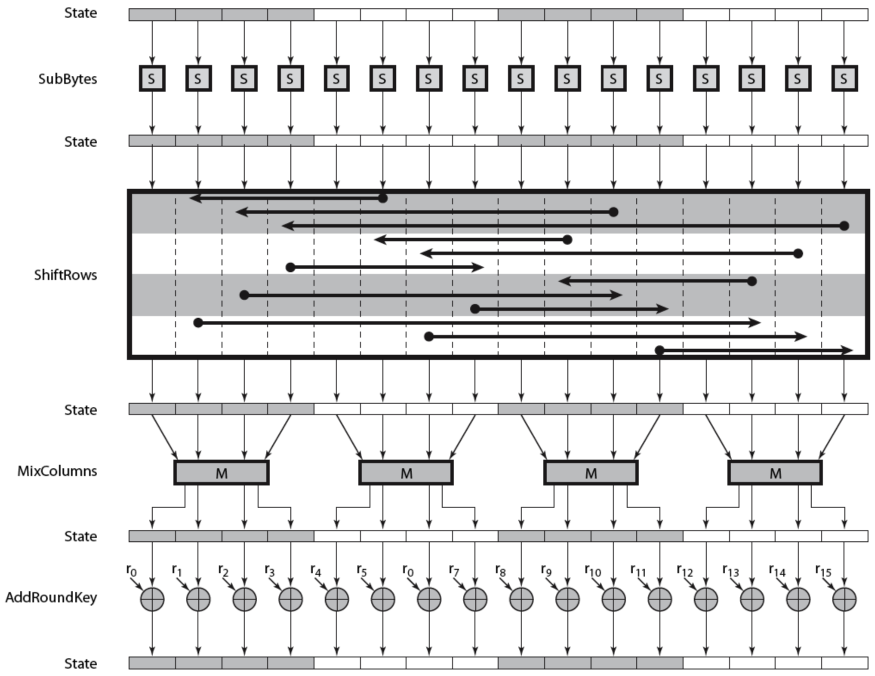
- XOR state with 128-bits of the round key
- AddRoundKey proceeds one column at a time.
  - adds a round key word with each state column matrix the operation is matrix addition
- Designed to be as simple as possible

AddRoundKey Scheme



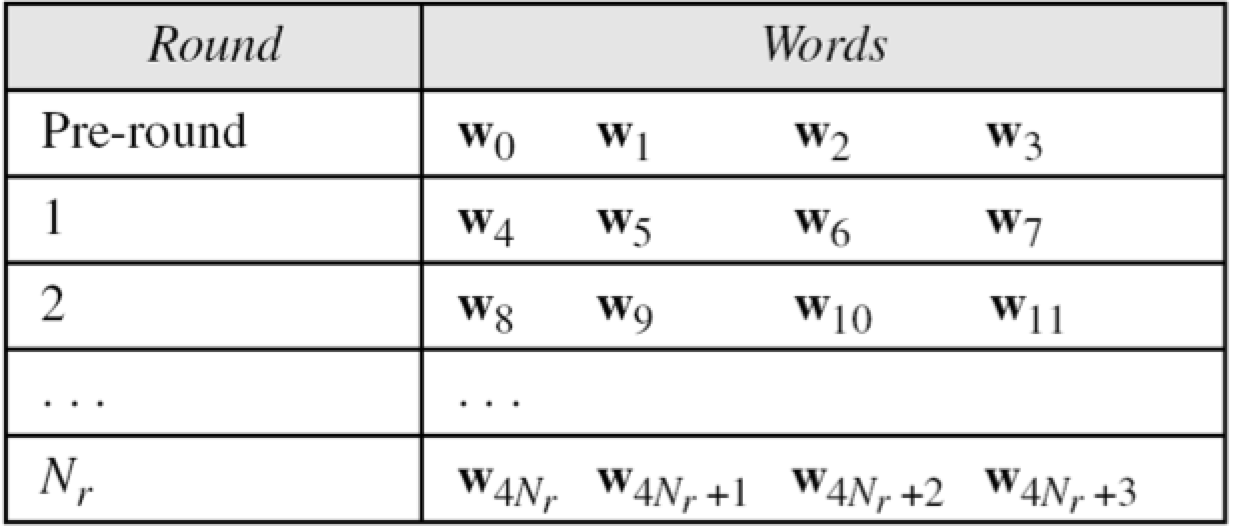
$$\begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} \oplus \begin{bmatrix} w_i & w_{i+1} & w_{i+2} & w_{i+3} \end{bmatrix} = \begin{bmatrix} s'_{0,0} & s'_{0,1} & s'_{0,2} & s'_{0,3} \\ s'_{1,0} & s'_{1,1} & s'_{1,2} & s'_{1,3} \\ s'_{2,0} & s'_{2,1} & s'_{2,2} & s'_{2,3} \\ s'_{3,0} & s'_{3,1} & s'_{3,2} & s'_{3,3} \end{bmatrix}$$

AES Round


State
SubBytes
S
State
ShiftRows
State
MixColumns
M
State
AddRoundKey
r_0 r_1 r_2 r_3 r_4 r_5 r_0 r_7 r_8 r_9 r_{10} r_{11} r_{12} r_{13} r_{14} r_{15}
State

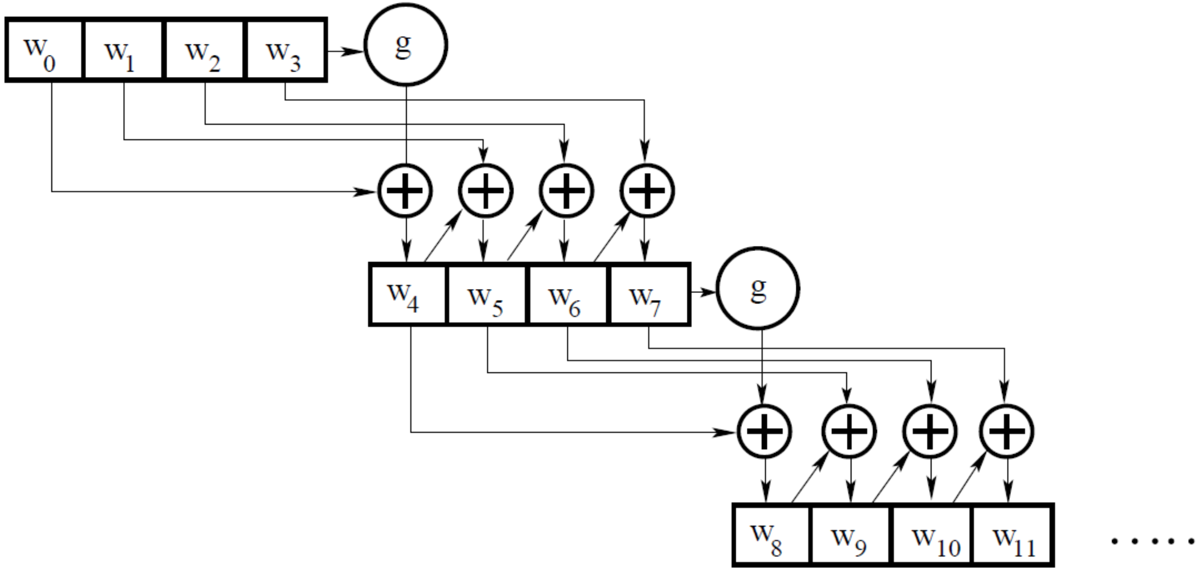
AES Key Scheduling

- takes 128-bits (16-bytes) key and expands into array of 44 32-bit words



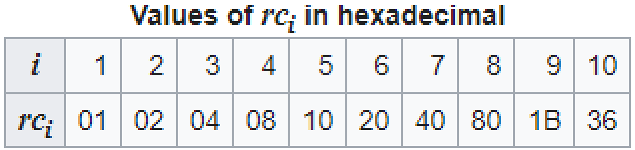
Round	*Words*			
Pre-round	$\mathbf{w}_0$	$\mathbf{w}_1$	$\mathbf{w}_2$	$\mathbf{w}_3$
1	$\mathbf{w}_4$	$\mathbf{w}_5$	$\mathbf{w}_6$	$\mathbf{w}_7$
2	$\mathbf{w}_8$	$\mathbf{w}_9$	$\mathbf{w}_{10}$	$\mathbf{w}_{11}$
. . .	. . .			
N_r	$\mathbf{w}_{4N_r}$	$\mathbf{w}_{4N_r+1}$	$\mathbf{w}_{4N_r+2}$	$\mathbf{w}_{4N_r+3}$

Key generation



Rcon

$$rc_i = \begin{cases} 1 & \text{if } i = 1 \\ 2 \cdot rc_{i-1} & \text{if } i > 1 \text{ and } rc_{i-1} < 80_{16} \\ (2 \cdot rc_{i-1}) \oplus 11\text{B}_{16} & \text{if } i > 1 \text{ and } rc_{i-1} \geq 80_{16} \end{cases}$$

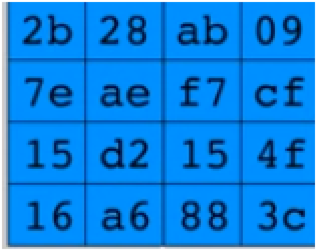


Values of rc_i in hexadecimal

i	1	2	3	4	5	6	7	8	9	10
rc_i	01	02	04	08	10	20	40	80	1B	36

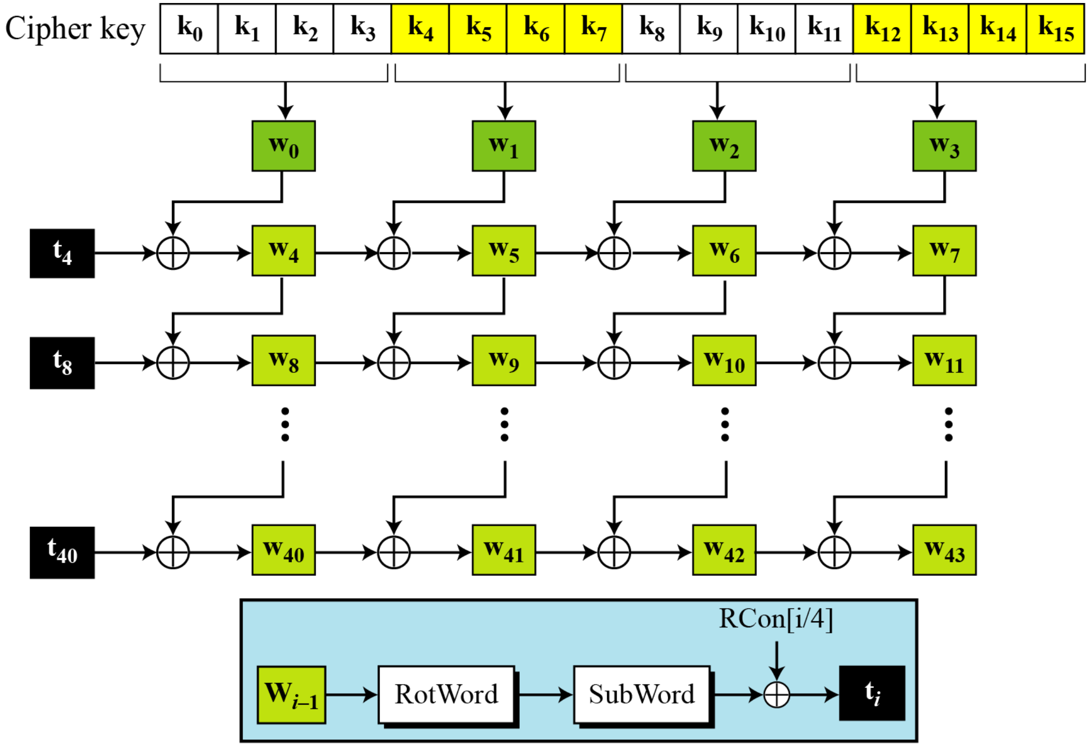
$$W_i = \begin{cases} K_i & \text{if } i < N \\ W_{i-N} \oplus \text{SubWord}(\text{RotWord}(W_{i-1})) \oplus rcon_{i/N} & \text{if } i \geq N \text{ and } i \equiv 0 \pmod{N} \\ W_{i-N} \oplus \text{SubWord}(W_{i-1}) & \text{if } i \geq N,\ N > 6, \text{ and } i \equiv 4 \pmod{N} \\ W_{i-N} \oplus W_{i-1} & \text{otherwise.} \end{cases}$$

AES key scheduling example



2b	28	ab	09
7e	ae	f7	cf
15	d2	15	4f
16	a6	88	3c

Key Expansion Scheme



Cipher key
k_0 k_1 k_2 k_3 k_4 k_5 k_6 k_7 k_8 k_9 k_{10} k_{11} k_{12} k_{13} k_{14} k_{15}
w_0 w_1 w_2 w_3
t_4 w_4 w_5 w_6 w_7
t_8 w_8 w_9 w_{10} w_{11}
t_{40} w_{40} w_{41} w_{42} w_{43}
W_{i-1}
RotWord
SubWord
RCon[i/4]
t_i

Making of t_i (temporary) words $i = 4\ N_r$

Key Expansion Example (1st Round)

- Example of expansion of a 128-bit cipher key

Cipher key = 2b7e151628aed2a6abf7158809cf4f3c

w0=2b7e1516 w1=28aed2a6 w2=abf71588 w3=09cf4f3c

i	w_{i-1}	RotWord	SubWord	Rcon[i/4]	t_i	w[i-4]	w_i
4	09cf4f3c	cf4f3c09	8a84eb01	01000000	8b84eb01	2b7e1516	a0fafe17
5	a0fafe17	-	-	-	-	28aed2a6	88542cb1
6	88542cb1	-	-	-	-	Abf71588	23a33939
7	23a33939	-	-	-	-	09cf4f3c	2a6c7605

AES Security

- AES was designed after DES.
- Most of the known attacks on DES were already tested on AES.
- Brute-Force Attack
  - AES is definitely more secure than DES due to the larger-size key.
- Statistical Attacks
  - Numerous tests have failed to do statistical analysis of the ciphertext
- Differential and Linear Attacks
  - There are no differential and linear attacks on AES as yet.

Implementation Aspects

- The algorithms used in AES are so simple that they can be easily implemented using cheap processors and a minimum amount of memory.
- Very efficient
- Implementation was a key factor in its selection as the AES cipher
- AES animation:
  - http://www.cs.bc.edu/~straubin/cs381-05/blockciphers/rijndael_ingles2004.swf

Thank you

Next Class

☞ Mandatory reading for the next class

  ☞ https://seedsecuritylabs.org/Labs_16.04/Crypto/Crypto_Encryption/

S Rajashree

Computer Science and Engineering

PES University, Bengaluru

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PESU Center for
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