Applied Cryptography and Computer Security

CSE 664 Spring 2017

Lecture 7: Advanced Encryption Standard (AES)

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Lecture Outline

- **Last time:**
  - **block ciphers**
  - **Data Encryption Standard**
  - **attacks on DES**
  - **double and triple DES**
- **This lecture:**
  - **Advanced Encryption Standard**
  - **cipher details**

Advanced Encryption Standard (AES)

- In 1997 NIST made a formal call for an unclassified publicly disclosed encryption algorithm available worldwide and royalty-free
  - the goal was to replace DES with a new standard called AES
  - the algorithm must be a symmetric block cipher
  - the algorithm must support (at a minimum) 128-bit blocks and key sizes of 128, 192, and 256 bits
- The evaluation criteria were:
  - security
  - speed and memory requirements
  - algorithm and implementation characteristics

AES

- **In 1998 15 candidate AES algorithms were announced**
- **They were narrowed to 5 in 1999: MARS, RC6, Rijndael, Serpent, and Twofish**
  - **all five were thought to be secure**
- **A more thorough evaluation was performed**
- **In 2000 NIST announced that Rijndael was selected as the AES**
- **In 2001 AES was published for public review and comments and adopted later that year (published in FIPS 197)**
- **The selection process for the AES was very open**

AES

- **Rijndael**
  - **invented by Belgian researchers Deamen and Rijmen**
  - **designed to be simple and efficient in both hardware and software on a wide range of platforms**
  - **supports different block sizes (128, 192, and 256 bits)**
  - **supports keys of different length (128, 192, and 256 bits)**
  - **uses a variable number of rounds**
    - $Nr = 10$ **if both keys and block sizes are 128**
    - $Nr = 12$ **if max of block and key sizes is 192**
    - $Nr = 14$ **if max of block and key sizes is 256**

AES

- **During encryption:**
  - **the block is copied into the state matrix**
  - **the state is modified at each round of encryption and decryption**
  - **the final state is copied to the ciphertext**

in_0	in_4	in_8	in_{12}
in_1	in_5	in_9	in_{13}
in_2	in_6	in_{10}	in_{14}
in_3	in_7	in_{11}	in_{15}

$\longrightarrow$

$s_{0,0}$	$s_{0,1}$	$s_{0,2}$	$s_{0,3}$
$s_{1,0}$	$s_{1,1}$	$s_{1,2}$	$s_{1,3}$
$s_{2,0}$	$s_{2,1}$	$s_{2,2}$	$s_{2,3}$
$s_{3,0}$	$s_{3,1}$	$s_{3,2}$	$s_{3,3}$

$\dashrightarrow$

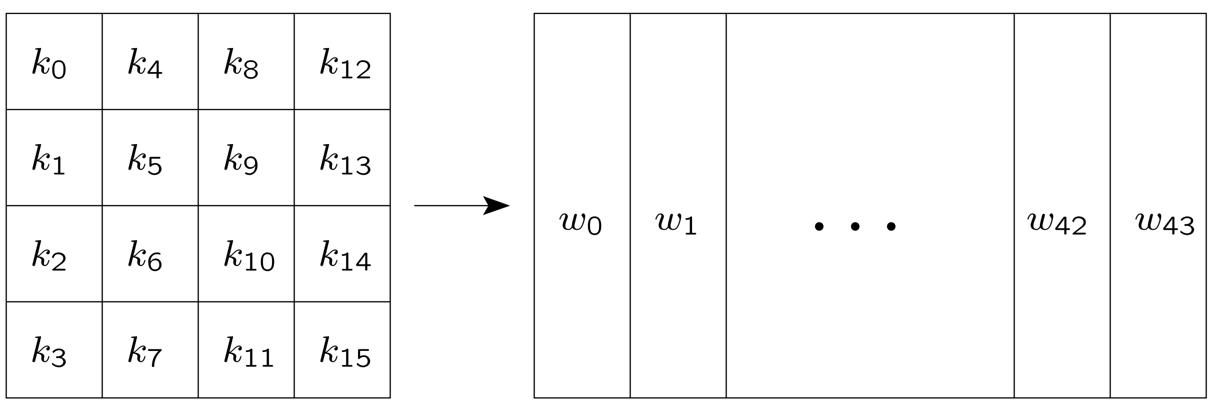
$s_{0,0}$	$s_{0,1}$	$s_{0,2}$	$s_{0,3}$
$s_{1,0}$	$s_{1,1}$	$s_{1,2}$	$s_{1,3}$
$s_{2,0}$	$s_{2,1}$	$s_{2,2}$	$s_{2,3}$
$s_{3,0}$	$s_{3,1}$	$s_{3,2}$	$s_{3,3}$

$\longrightarrow$

out_0	out_4	out_8	out_{12}
out_1	out_5	out_9	out_{13}
out_2	out_6	out_{10}	out_{14}
out_3	out_7	out_{11}	out_{15}

AES

- **The key schedule in AES**
  - **the key is treated as a 4×4 matrix as well**
  - **the key is then expanded into an array of words**
  - **each word is 4 bytes and there are 44 words (for 128-bit key)**
  - **four distinct words serve as a round key for each round**



AES

- **Rijndael doesn't have a Feistel structure**
  - **2 out of 5 AES candidates (including Rijndael) don't use Feistel structure**
  - **they process the entire block in parallel during each round**
- **The operations are (3 substitution and 1 permutation operations):**
  - SUBBYTES: **byte-by-byte substitution using an S-box**
  - SHIFTROWS: **a simple permutation**
  - MIXCOLUMNS: **a substitution using mod** 2^8 **arithmetics**
  - ADDROUNDKEY: **a simple XOR of the current state with a portion of the expanded key**

AES

- **At a high-level, encryption proceeds as follows:**
  - **set initial state** $s_0 = m$
  - **perform operation** AddRoundKey **(XORs** k_i **and** s_i**)**
  - **for each of the first** $Nr - 1$ **rounds:**
    - **perform a substitution operation** SubBytes **on** s_i **and an S-box**
    - **perform a permutation** ShiftRows **on** s_i
    - **perform an operation** MixColumns **on** s_i
    - **perform** AddRoundKey
  - **the last round is the same except no** MixColumns **is used**
  - **set the ciphertext** $c = s_{Nr}$

AES

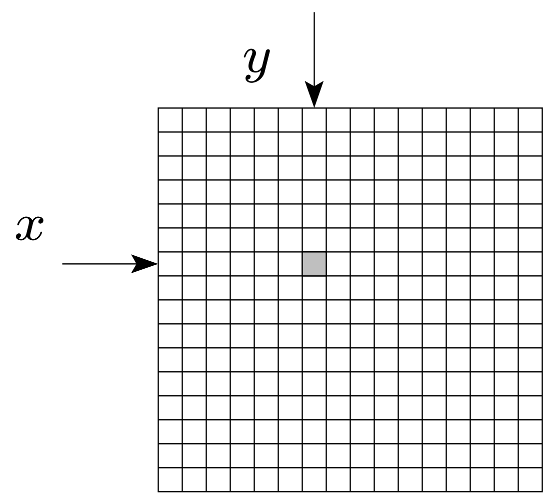
- **More about Rijndael design...**
  - **ADDROUNDKEY is the only operation that uses key**
    - **that's why it is applied at the beginning and at the end**
  - **all operations are reversible**
  - **the decryption algorithm uses the expanded key in the reverse order**
  - **the decryption algorithm, however, is not identical to the encryption algorithm**

AES

- **The SubBytes operation**
  - **maps a state byte $s_{i,j}$ to a new byte $s'_{i,j}$ using S-box**
  - **the S-box is a 16×16 matrix with a byte in each position**
    - **the S-box contains a permutation of all possible 256 8-bit values**
    - **the values are computed using a formula**
    - **it was designed to resist known cryptanalytic attacks (i.e., to have low correlation between input bits and output bits)**

AES

- The SubBytes operation
  - to compute the new $s'_{i,j}$:
    - set x to the 4 leftmost bits of $s_{i,j}$ and y to its 4 rightmost bits
    - use x as the row and y as the column to locate a cell in the S-box
    - use that cell value as $s'_{i,j}$



  - the same procedure is performed on each byte of the state

AES

- **The ShiftRows operation**
  - **performs circular left shift on state rows**
    - **2nd row is shifted by 1 byte**
    - **3rd row is shifted by 2 bytes**
    - **4th row is shifted by 3 bytes**

$s_{0,0}$	$s_{0,1}$	$s_{0,2}$	$s_{0,3}$
$s_{1,0}$	$s_{1,1}$	$s_{1,2}$	$s_{1,3}$
$s_{2,0}$	$s_{2,1}$	$s_{2,2}$	$s_{2,3}$
$s_{3,0}$	$s_{3,1}$	$s_{3,2}$	$s_{3,3}$

→

$s_{0,0}$	$s_{0,1}$	$s_{0,2}$	$s_{0,3}$
$s_{1,1}$	$s_{1,2}$	$s_{1,3}$	$s_{1,0}$
$s_{2,2}$	$s_{2,3}$	$s_{2,0}$	$s_{2,1}$
$s_{3,3}$	$s_{3,0}$	$s_{3,1}$	$s_{3,2}$

  - **important because other operations operate on a single cell**

AES

- **The** MixColumns **operation**
  - **multiplies the state by a fixed matrix**

$$\begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} = \begin{bmatrix} s'_{0,0} & s'_{0,1} & s'_{0,2} & s'_{0,3} \\ s'_{1,0} & s'_{1,1} & s'_{1,2} & s'_{1,3} \\ s'_{2,0} & s'_{2,1} & s'_{2,2} & s'_{2,3} \\ s'_{3,0} & s'_{3,1} & s'_{3,2} & s'_{3,3} \end{bmatrix}$$

  - **was designed to ensure good mixing among the bytes of each column**
  - **the coefficients 01, 02, and 03 are for implementation purposes (multiplication involves at most a shift and an XOR)**

AES

- **Decryption:**
  - **inverse S-box is used in** SUBBYTES
  - **inverse shifts are performed in** SHIFTROWS
  - **inverse multiplication matrix is used in** MIXCOLUMNS
- **Key expansion:**
  - **was designed to resist known attacks and be efficient**
  - **knowledge of a part of the key or round key doesn't enable calculation of other key bits**
  - **round-dependent values are used in key expansion**

AES

- **Summary of Rijndael design**
  - **simple design but resistant to known attacks**
  - **very efficient on a variety of platforms including 8-bit and 64-bit platforms**
  - **highly parallelizable**
  - **had the highest throughput in hardware among all AES candidates**
  - **well suited for restricted-space environments (very low RAM and ROM requirements)**
  - **optimized for encryption (decryption is slower)**

Encryption Modes

- **Recall that encryption modes specify how messages longer than one block are encrypted and decrypted**
- **4 modes of operation were standardized in FIPS Pub. 81 for DES**
  - **electronic codebook mode (ECB), cipher feedback mode (CFB), cipher block chaining mode (CBC), and output feedback mode (OFB)**
- **5 modes have been approved by NIST for AES and other ciphers in 2001**
  - **the 4 above and counter mode**

Bootstrapping Symmetric Encryption

- You can communicate a secret key to your friend by:
  - phone, (slow) mail, inviting her for dinner, ...
- We are going to use public key encryption to communicate the symmetric encryption key
- To agree on a secret symmetric key, the idea is:
  - pick a fresh secret key s and encrypt it with the friend's publicly known key pk as $\mathsf{Enc}_{pk}(s)$
  - the friend will be able to decrypt and use s, but nobody else