Lecture 5

Encryption Continued...

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Why not 2-DES ?

- 2DES: $C = DES(K1, DES(K2, P))$
- Seems to be hard to break by "brute force", approx. 2^{111} trials
- Assume Eve is trying to break 2DES and has a single (P,C) pair

Meet-in-the-middle (or Rendesvouz) ATTACK:

I. For each possible K'_i (where $0 < i < 2^{56}$)
   1. Compute $C'_i = DES(K'_i, P)$
   2. Store: $[K'_i, C'_i]$ in table T (sorted by C'_i)

II. For each possible K''_i (where $0 < i < 2^{56}$)
   1. Compute $C''_i = DES^{-1}(K''_i, C)$
   2. Lookup C''_i in T $\leftarrow$ not expensive!
   3. If lookup succeeds, output: $K1=K'_i$, $K2=K''_i$

TOTAL COST: $O(2^{56})$ operations + $O(2^{56})$ storage

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DES Variants

- 3-DES (triple DES)
  - *C* = E(K1, D(K2, E(K1,P))) → 112 effective key bits
  - *C* = E(K3, D(K2, E(K1,P))) → 168 effective key bits
- DESx
  - *C*= K3 XOR E(K2, (K1 XOR P)) → seems like 184 key bits
  - Effective key bits → approx. 118
- 2-DES:
  - *C* = E(K2,E(K1, P)) → rendezvous (meet-in-the-middle attack)
- Another simple variation:
  - *C* = K1 XOR E(K1', P) → weak!

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DES Variants

Why does 3-DES (or generally n-DES) work?

Because, as a function, DES is not a group…

A "group" is an algebraic structure. One of its properties is that, taking any 2 elements of the group (a,b) and applying an operator F() yields another element c in the group.

Suppose: *C* = DES(K1,DES(K2,P))

There is no K, such that:

for each possible plaintext P, DES(K,P) = *C*

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DES summary

- Permutation/substitution block cipher
- 64-bit data blocks
- 56-bit keys (8 parity bits)
- 16 rounds (shifts, XORs)
- Key schedule
- S-box selection secret…

- DES "aging"
- 2-DES: rendezvous attack
- 3-DES: 112-bit security
- DESx : 118-bit security

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Other Symmetric Ciphers

Skipjack
- Classified algorithm originally designed for Clipper,
- declassified in 1998
- 32 rounds, breakable with 31 rounds
- 80 bit key, inadequate for long-term security

GOST
- GOST 28147, Russian answer to DES
- 32 rounds, 256 bit key
- Incompletely specified

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Other Symmetric Ciphers

- IDEA (X. ILai, J. Massey, ETH)
  - Developed as PES (proposed encryption standard),
  - adapted to resist differential cryptanalysis
  - Gained popularity via PGP, 128 bit key
  - Patented (Ascom CH)

- Blowfish (B. Schneier, Counterpane)
  - Optimized for high-speed execution on 32-bit processors
  - 448 bit key, relatively slow key setup
  - Fast for bulk data on most PCs/laptops
  - Easy to implement, runs in ca. 5K of memory

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Other Symmetric Ciphers

RC4 (Ron's Cipher #4) Stream cipher:

- **Optimized for fast software implementation**
- **Character streaming (not bit)**
- **8-bit output**
- **Former trade secret of RSADSI,**
- **Reverse-engineered and posted to the net in 1994:**
- **2048-bit key**
- **Used in many products until about 1999-2000**

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Other Symmetric Ciphers (RC4)

```
x=y=0;
while( length-- )
{       /* state[0-255] contains key bytes */
    sx = state[ ++x & 0xFF ];
    y += sx & 0xFF;
    sy = state[ y ];
    state[ y ] = sx;
    state[ x ] = sy;
    *data++ ^= state[ ( sx+sy ) & 0xFF ];
}
```

Takes about a minute to implement from memory

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Other Symmetric Ciphers

- **RC5**
  - Suitable for hardware and software
  - Fast, simple
  - Adaptable to processors of different word lengths
  - Variable number of rounds
  - Variable-length key (0-256 bytes)
  - Very low memory requirements
  - High security (no effective attacks, yet…)
  - Data-dependent rotations

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Other Symmetric Ciphers

- RC5 single round pseudocode:

$$
\begin{aligned}
L &\leftarrow L \text{ XOR } R \\
L &\leftarrow L <<< R \\
L &\leftarrow L + \text{subkey}[2i] \\
R &\leftarrow R \text{ XOR } L \\
R &\leftarrow R <<< L \\
R &\leftarrow R + \text{subkey}[2i+1]
\end{aligned}
$$

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AES:

The Rijndael Block Cipher

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Introduction and History

- National Institute of Science and Technology (NIST) regulates standardization in the US
- DES is an aging standard that no longer meets today's needs for strong encryption
- Triple-DES: Endorsed by NIST as a "de facto" standard
- AES: Advanced Encryption Standard
  - Finalized in 2001
  - Goal is to define the Federal Information Processing Standard (FIPS) by selecting a new encryption algorithm suitable for encrypting (non-classified non-military) government documents
  - Candidate algorithms must be:
    - Symmetric-key ciphers supporting 128, 192, and 256 bit keys
    - Royalty-Free
    - Unclassified (i.e. public domain)
    - Available for worldwide export

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Introduction and History

- AES Round-3 Finalist Algorithms:
  - MARS
    - Candidate offering from IBM Research
  - RC6
    - By Ron Rivest of MIT & RSA Labs, creator of the widely used RC4/RC5 algorithm and "R" in RSA
  - Twofish
    - From Counterpane Internet Security, Inc. (MN)
  - Serpent
    - by Ross Anderson (UK), Eli Biham (ISR) and Lars Knudsen (NO)
  - Rijndael
    - by Joan Daemen and Vincent Rijmen (B)

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Rijndael

The Winner: Rijndael

- Joan Daemen (of Proton World International) and Vincent Rijmen (of Katholieke Universiteit Leuven).
- pronounced “Rhine-doll”
- Allows only 128, 192, and 256-bit key sizes (unlike other candidates)
- Variable input block length: 128, 192, or 256 bits. All nine combinations of key-block length possible.
  - *A block is the smallest data size the algorithm will encrypt*
- Vast speed improvement over DES in both hw and sw implementations
  - 8,416 bytes/sec on a 20MHz 8051
  - 8.8 Mbytes/sec on a 200MHz Pentium Pro

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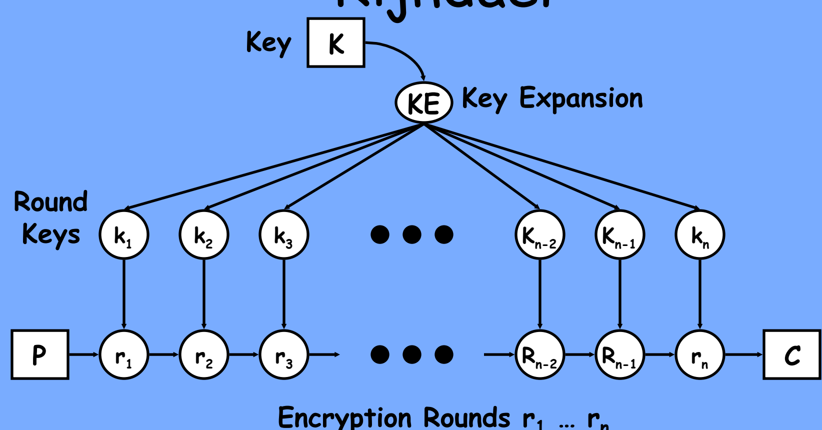
Rijndael



- Key is expanded to a set of n round keys
- Input block P put thru n rounds, each with a distinct round sub-key.
- Strength of algorithm relies on difficulty of obtaining intermediate results (or *state*) of round i from round i+1 without the round key.

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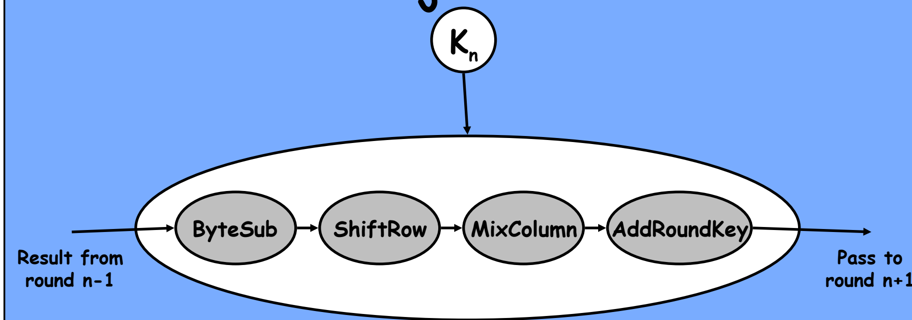
Rijndael



<u>**Detailed view of round n**</u>

- **Each round performs the following operations:**
  - **Non-linear Layer: No linear relationship between the input and output of a round**
  - **Linear Mixing Layer: Guarantees high diffusion over multiple rounds**
    - **Very small correlation between bytes of the round input and the bytes of the output**
  - **Key Addition Layer: Bytes of the input are simply XOR'ed with the expanded round key**

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Rijndael

- Three layers provide strength against known types of cryptographic attacks: Rijndael provides "full diffusion" after only two rounds
- Immune to:
  - Linear and differential cryptanalysis
  - Related-key attacks
  - Square attack
  - Interpolation attacks
  - Weak keys
- Rijndael has been "shown" *secure*:
  - No key recovery attacks faster than exhaustive search exist
  - No known symmetry properties in the round mapping
  - No weak keys identified
  - No related-key attacks: No two keys have a high number of expanded round keys in common

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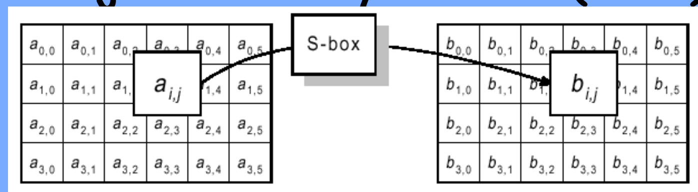
Rijndael: ByteSub (192)



Each byte at the input of a round undergoes a non-linear byte substitution according to the following transform:

$$
\begin{bmatrix} y_0 \\ y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}
\begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} +
\begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}
$$

Substitution ("S")-box

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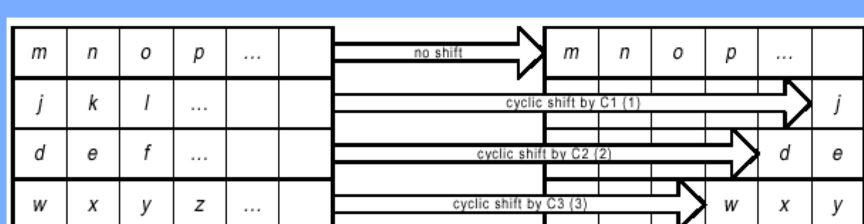
Rijndael: ShiftRow

Nb	C1	C2	C3
4	1	2	3
6	1	2	3
8	1	3	4

Depending on the block length, each "row" of the block is cyclically shifted according to the above table



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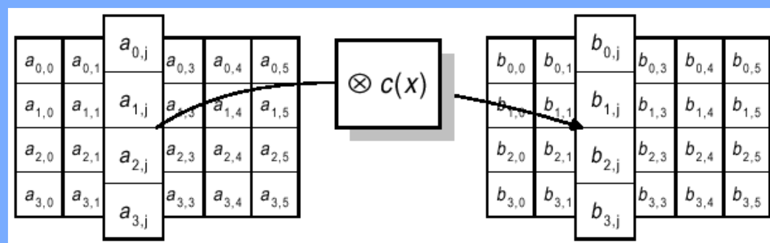
Rijndael: MixColumn



Each column is multiplied by a fixed polynomial
C(x) = '03'*X^3 + '01'*X^2 + '01'*X + '02'

This corresponds to matrix multiplication b(x) = c(x) ⊗ a(x):

$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

Not xor

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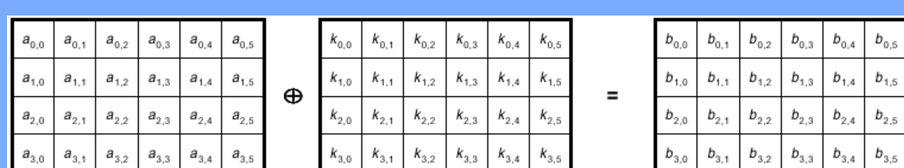
Rijndael: Key Expansion and Addition



Each word is simply XOR'ed with the expanded round key

Key Expansion algorithm:

```
KeyExpansion(int* Key[4*Nk], int* EKey[Nb*(Nr+1)])
{
    for(i = 0; i < Nk; i++)
        EKey[i] = (Key[4*i],Key[4*i+1],Key[4*i+2],Key[4*i+3]);
    for(i = Nk; i < Nb * (Nr + 1); i++)
    {
        temp = EKey[i - 1];
        if (i % Nk == 0)
            temp = SubByte(RotByte(temp)) ^ Rcon[i / Nk];
        EKey[i] = EKey[i - Nk] ^ temp;
    }
}
```

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Rijndael: Implementations

- Well-suited for software implementations on 8-bit processors (important for "Smart Cards")
  - Atomic operations focus on bytes and nibbles, not 32- or 64-bit integers
  - Layers such as ByteSub can be efficiently implemented using small tables in ROM (e.g. < 256 bytes).
  - No special instructions are required to speed up operation, e.g. barrel rotates
- For 32-bit implementations:
  - An entire round can be implemented via a fast table lookup routine on machines with 32-bit or higher word lengths
  - Considerable parallelism exists in the algorithm
    - Each layer of Rijndael operates in a parallel manner on the bytes of the round state, all four component transforms act on individual parts of the block
    - Although the Key expansion is complicated and cannot benefit much from parallelism, it only needs to be performed *once* until the two parties switch keys.

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Rijndael: Implementations

- Hardware Implementations
  - Rijndael performs very well in software, but there are cases when better performance is required (e.g. server and VPN applications).
  - Multiple S-Box engines, round-key XORs, and byte shifts can all be implemented efficiently in hardware when absolute speed is required
  - Small amount of hardware can vastly speed up 8-bit implementations
- Inverse Cipher
  - Except for the non-linear ByteSub step, each part of Rijndael has a straightforward inverse and the operations simply need to be undone in the reverse order.
  - However, Rijndael was specially written so that the same code that encrypts a block can also decrypt the same block simply by changing certain tables and polynomials for each layer. The rest of the operation remains identical.

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Conclusions and The Future

- Rijndael is an extremely fast, state-of-the-art, highly secure algorithm
- Amenable to efficient implementation in both hw and sw; requires no special instructions to obtain good performance on any computing platform
- Triple-DES, still highly secure and supported by NIST, is expected to be common for the foreseeable future.

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Reminder: World's best cipher!

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One-time pad

For each character:

	0	1	1	1	0	0	1	0	1	1	0	← pad (key)
$\oplus$	1	1	0	0	0	1	1	1	0	1	0	← msg (plaintext)
	1	0	1	1	0	1	0	1	1	0	0	← ciphertext (encrypted msg)

One-time pad (cont.)

- **Symmetric**
- **Pad is selected at random**
- **Pad is as long as plaintext**
- **Perfectly secure, but...**
- **One time only:**

  so sending the pad is just as hard as sending the msg

A more realistic version: Pseudo-random OTP

Pseudo-random bit string (**PRBS**) *generator:*

seed *(short)* *01101* → PRBS → 1010010110.... → **string** *(long)*

Computationally Hard *to guess a bit (after seeing many others)*

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