Block ciphers and AES

Cryptology, 2016 Autumn

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September 27, 2016

Outline

Introduction

Block cipher model and security definition

Data Encryption Standard (DES)

Advanced Encryption Standard (AES)

Encryption modes of block ciphers

Authentication modes of block ciphers

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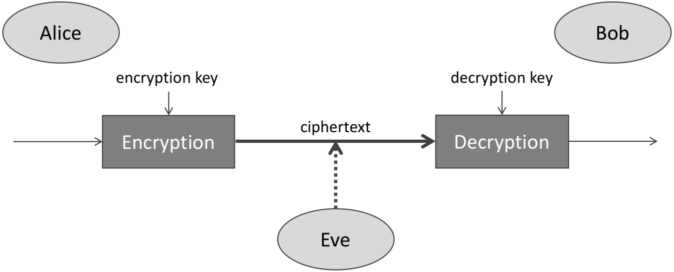
Encryption



- Alice: sender, enciphers message to cryptogram using key
- Bob: receiver, deciphers cryptogram to message using key
- Eve: eavesdropper, does not have key

The one-time pad

message =	0	1	0	1	1	1	0	1	
keystream =	1	1	1	1	0	0	0	0	$\oplus$
cryptogram =	1	0	1	0	1	1	0	1	

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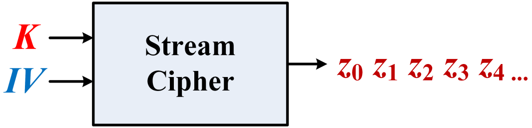
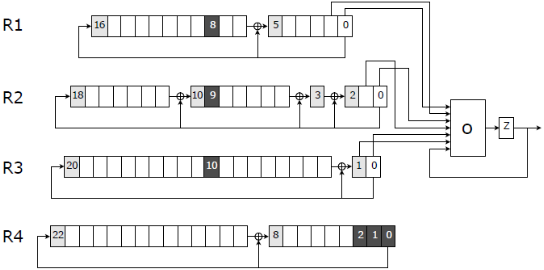
Provably secure if keystream is *fully random*

Stream cipher



- Generates keystream bits z_t from
  - K: secret, typically 128 or 256 bits
  - IV: initial value, for generating multiple keystreams per key
- z_t can be a bit or a sequences of bits, e.g. a 32-bit word

Example: DECT Stream Cipher



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- 4 LFSRs with coprime lengths: large period
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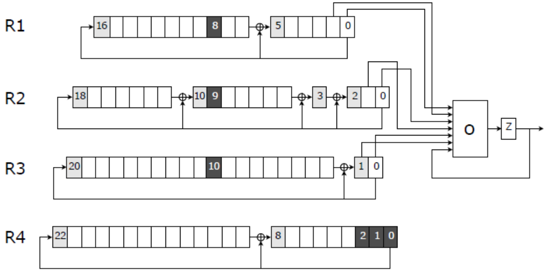

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- 4 LFSRs with coprime lengths: large period
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- practically broken with statistical key recovery attack

Example: RC4 [Ron Rivest] stream cipher

- State is array of 256 bytes
- Simple and elegant update function and output function
- Software-oriented

```
i := 0
j := 0
while GeneratingOutput:
    i := (i + 1) mod 256
    j := (j + S[i]) mod 256
    swap values of S[i] and S[j]
    K := S[(S[i] + S[j]) mod 256]
    output K
endwhile
```

- Used in TLS and WEP
- Biases in keystream
- Practically broken in several use cases

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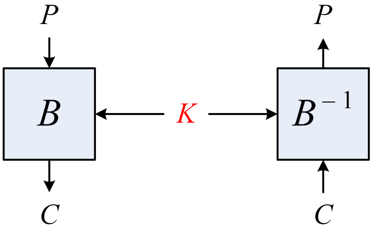

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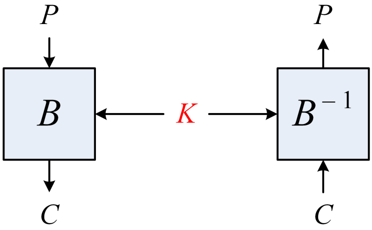

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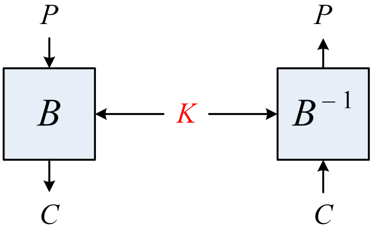

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  - infeasible otherwise

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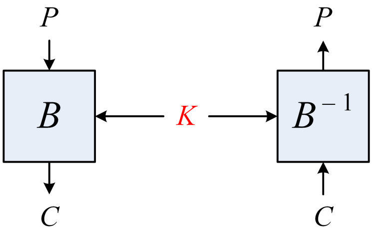

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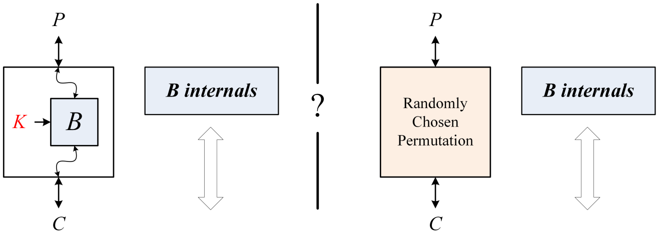
- Dimensions: block length b and key length

Pseudorandom Permutation (PRP) security



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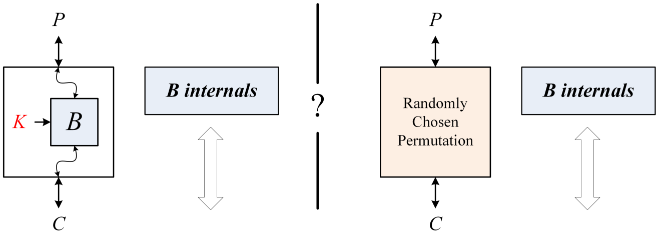

- Infeasibility to distinguish $B[K]$ from random permutation
- Distinguishing should have expected effort that is out of reach

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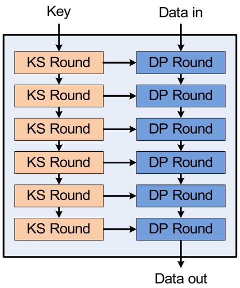

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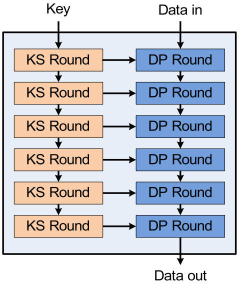

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  - iteration of a non-linear round function
  - ...that depends on a round key

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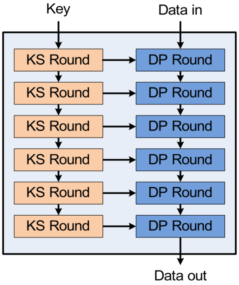
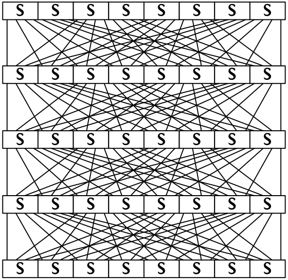


- Data path (right): transforms P to C
  - iteration of a non-linear round function
  - ...that depends on a round key
- Key schedule (left)
  - generates round keys from cipher key K

Substitution-permutation network (SPN)



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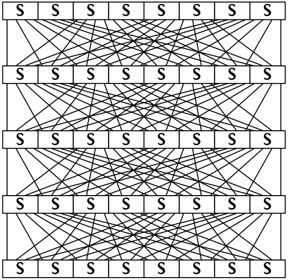

Round function in data path with two (or three) layers

- Non-linear substitution layer: S-boxes applied in parallel
- permutation layer: moves bits to different S-box positions
- either key-dependent S-boxes or third layer of *key addition*

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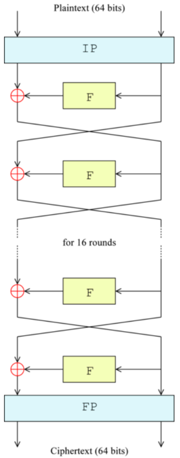
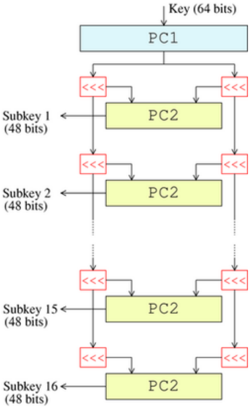
  - freely usable
- Massively adopted by banks and industry worldwide
- Dominated symmetric crypto for more than 20 years

Data encryption standard: overview

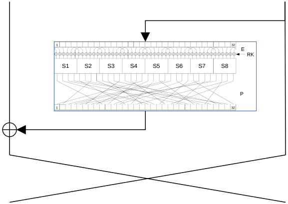
Feistel data path



Linear key schedule



Data encryption standard: F-function



- Variant of SPN with 4 layers:

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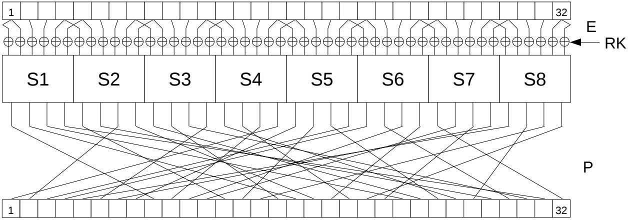

- Variant of SPN with 4 layers:
  - expansion E: from 32 to 48 bits
  - bitwise round key addition
  - substitution: 8 different 6-to-4 bit non-linear S-boxes
  - permutation P: moving nearby bits to remote positions
- clearly hardware-oriented

Non-ideal DES property: Weak Keys

- What happens if the cipher key is all-zero?
  - all round keys are all-zero
  - all rounds are the same
  - cipher and its inverse are the same
- Same is true for an all-one cipher key
- And two more keys due to symmetry in key schedule
- Weak key K_w:

$$\mathsf{DES}[K_w] \circ \mathsf{DES}[K_w] = \mathrm{I}$$

- Also 6 semi-weak key pairs (K_1, K_2)

$$\mathsf{DES}[K_1] \circ \mathsf{DES}[K_2] = \mathrm{I}$$

- Mostly of academic interest

Non-ideality in DES: Complementation Property

- What happens if we complement the cipher input?
  - flip all bits in key
  - flip all bits in plaintext
- In first round
  - input to F complemented so output of E complemented
  - round key also complemented so input to S-boxes unaffected
  - output of F unaffected
- Output of first round is simply complemented
- Repeat this until you reach the ciphertext
- Complementation property:

$$\mathrm{DES}[K](P) = C \Leftrightarrow= \mathrm{DES}[\overline{K}](\overline{P}) = \overline{C}$$

- Reduces complexity of exhaustive key search from 2^{55} to 2^{54}

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Non-ideal DES properties: statistical attacks

- Two specific key-recovery attacks:
  - differential cryptanalysis: exploits difference propagation
  - linear cryptanalysis: exploits large P-to-C correlations
- Differential cryptanalysis [Biham and Shamir, 1990]
  - propag. of plaintext difference Δ_p to ciphertext difference Δ_c
  - $\mathrm{DP}(\Delta_p, \Delta_a)$: probability that Δ_p results in Δ_c
  - $\exists \Delta_p, \Delta_c$ with $\mathrm{DP}(\Delta_p, \Delta_a)$ relatively high for all keys
  - requires $|Q_s| \approx 2^{47}$ (1000 TeraByte) chosen plaintexts
- Linear cryptanalysis [Matsui, 1992]
  - correlation between bits in plaintext $u_p^{\mathrm{T}} p$ and ciphertext $u_c^{\mathrm{T}} c$
  - $\mathsf{Corr}(u_p, u_a)$: correlation between $u_p^{\mathrm{T}} p$ and $u_c^{\mathrm{T}} c$
  - $\exists u_p, u_c$ with $\mathsf{Corr}(u_p, u_c)$ relatively high for all keys
  - requires about $|Q_s| \approx 2^{43}$ (64 TeraByte) known plaintexts
- Both *break* DES but still non-trivial to exploit in the field

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- Exhaustive key search: about 3.6×10^{14} trials
- More than 15 years ago: "software" cracking
  - about 10.000 workstations
  - 500.000 trials per second per workstation
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- Short DES key is real-world concern!

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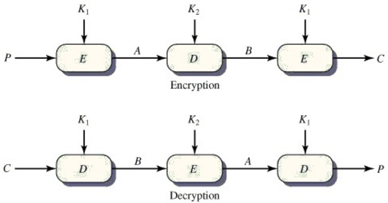
The solution: Triple DES (FIPS 46-2 and 46-3)



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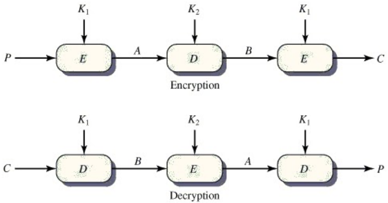

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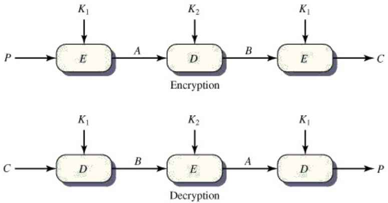

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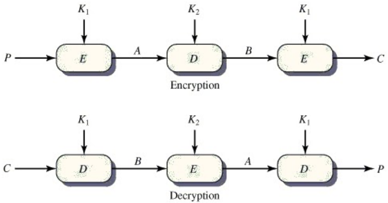

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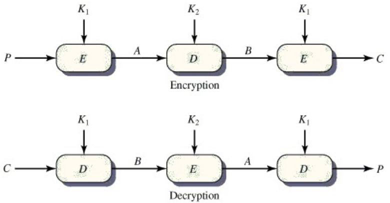

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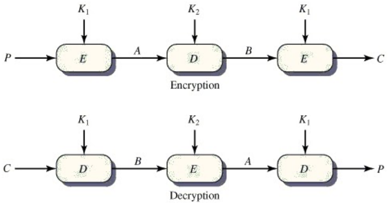

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    - still massively deployed by banks worldwide
  - 1-key: 56-bit key by taking $K_3 = K_2 = K_1$
    - falls back to single DES thanks to inverse in middle

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AES: the result of a competition

- January 1997: NIST announces the AES initiative
  - replacement of DES
  - open call for block cipher proposals
  - ...and for analysis, comparisons, etc.
- September 1997: official request for proposals
  - *faster than Triple-DES*
  - 128-bit blocks, 128-, 192- and 256-bit keys
  - specs, reference and optimized code, test vectors
  - design rationale and preliminary analysis
  - patent waiver
- Vincent Rijmen and I decided to submit a variant of Square
  - Most important change: multiple key and block lengths
  - We call it Rijndael

The AES competition

- First round: August 1998 to August 1999
  - 15 candidates at 1st AES conference in Ventura, California
  - analysis presented at 2nd AES conf. in Rome, March 1999
  - NIST narrowed down to 5 finalists using this analysis
- Second round: August 1999 to summer 2000
  - analysis presented at 3rd AES conf. in New York, April 2000
  - NIST selected winner using this analysis
- Criteria
  - security margin
  - efficiency in software and hardware
  - key agility
  - simplicity
- NIST motivated their choice in two reports

Rijndael design approach: the wide trail strategy

- Round function with four layers, each with separate goal:
  - nonlinear layer: S-boxes with high non-linearity
  - dispersion layer: like P in DES F-function
  - mixing layer (absent in DES): linear local mixing
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- Quality of mixing layer quantitied its branch number $\mathcal{B}$
  - allows proving bounds related to resistance against LC/DC
  - in combination with S-box layer and transposition layer
  - link with theory of error-correcting codes
  - optimum mix layer = maximum-distance-separable (MDS) code

Rijndael

- Block cipher with block and key lengths $\in \{128, 160, 192, 224, 256\}$
  - set of 25 block ciphers
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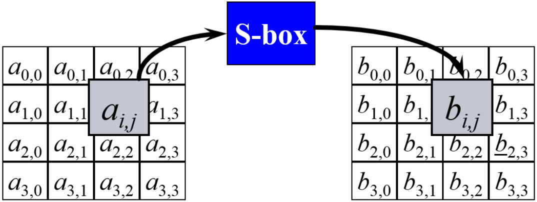
- Manipulates bytes with simple operations in $GF(2^8)$

The non-linear layer: SubBytes



Single S-box with two layers:

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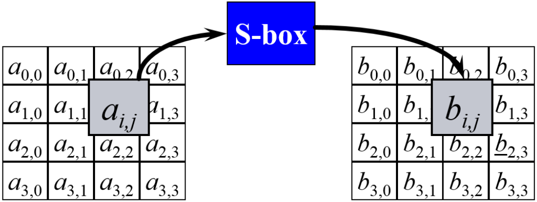

Single S-box with two layers:

- $y = x^{254}$ in GF(2^8)
  - $x^{\#x} = 1$ (Lagrange) so $y = x^{-1}$ for $x \neq 0$
  - optimal non-linearity [Nyberg, Eurocrypt 1993]

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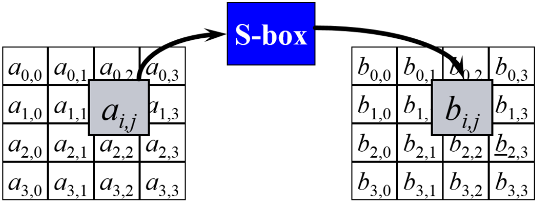

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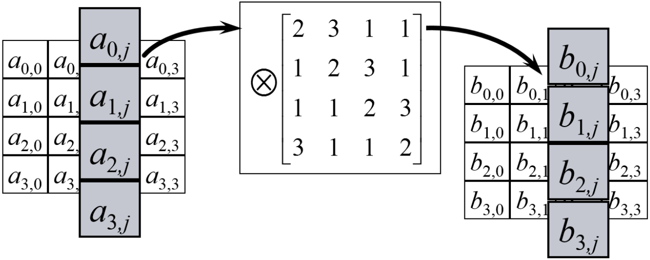
  - optimal non-linearity [Nyberg, Eurocrypt 1993]
- Affine mapping: multiplication by 8×8 matrix in GF(2)
  - to have algebraic complexity, without it: $xy = 1$ for $x \neq 0$

The mixing layer: MixColumns



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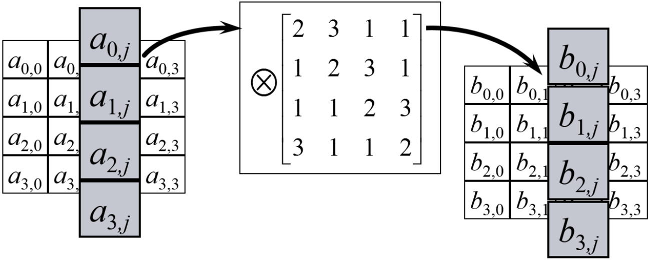
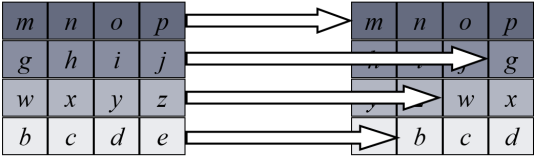


- Same mapping applied to all 4 columns
- Multiplication by a 4×4 circulant matrix in GF(2^8)
  - Elements: 1, 1, x and $x + 1$
  - *circulant MDS ($\mathcal{B} = 5$) matrix with the simplest elements*
  - Inverse has more complex elements

The dispersion layer: ShiftRows



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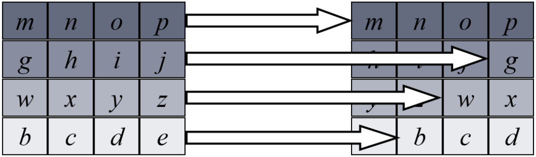

- Each row is shifted by a different amount
- Different shift offsets for higher block lengths
- Together with MixColumns and SubBytes:
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  - full diffusion in two rounds
  - $\mathcal{B}^2 = 25$ *active S-boxes in 4 rounds*

Round key addition: AddRoundKey

$$\begin{array}{|c|c|c|c|}\hline a_{0,0} & a_{0,1} & a_{0,2} & a_{0,3} \\ \hline a_{1,0} & a_{1,1} & a_{1,2} & a_{1,3} \\ \hline a_{2,0} & a_{2,1} & a_{2,2} & a_{2,3} \\ \hline a_{3,0} & a_{3,1} & a_{3,2} & a_{3,3} \\ \hline \end{array} + \begin{array}{|c|c|c|c|}\hline k_{0,0} & k_{0,1} & k_{0,2} & k_{0,3} \\ \hline k_{1,0} & k_{1,1} & k_{1,2} & k_{1,3} \\ \hline k_{2,0} & k_{2,1} & k_{2,2} & k_{2,3} \\ \hline k_{3,0} & k_{3,1} & k_{3,2} & k_{3,3} \\ \hline \end{array} = \begin{array}{|c|c|c|c|}\hline b_{0,0} & b_{0,1} & b_{0,2} & b_{0,3} \\ \hline b_{1,0} & b_{1,1} & b_{1,2} & b_{1,3} \\ \hline b_{2,0} & b_{2,1} & b_{2,2} & b_{2,3} \\ \hline b_{3,0} & b_{3,1} & b_{3,2} & b_{3,3} \\ \hline \end{array}$$

Key schedule: 192-bit key, 128-bit block example

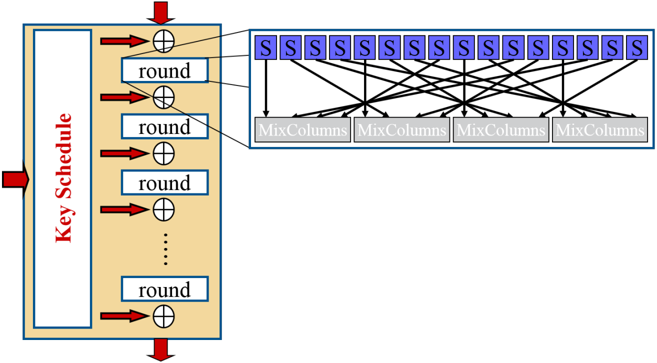
k_0	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	k_{14}	k_{15}	$\cdots$

Round key 0	Round key 1	Round key 2	$\cdots$

$$
\begin{aligned}
k_{6n} &= k_{6n-6} \oplus f(k_{6n-1}) \\
k_i &= k_{i-6} \oplus k_{i-1}, \quad i \neq 6n
\end{aligned}
$$

f: AES S-box in parallel to 4 bytes followed by cyclic shift over 1 byte

Rijndael: summary



- $\#$ rounds: $6 + \max(\ell_k, \ell_b)$ with ℓ_k key and ℓ_b block length in 32-bit words
- last round has no MixColumns to make inverse similar to cipher

Rijndael symmetry

- Highly symmetric round function (as opposed DES)
  - SubBytes: 1 S-box instead of different ones
  - MixColumns: 1 MDS matrix with circulant symmetry
  - ShiftRows: bytes relative movement independent of position
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  - called tower fields
- Asymmetry:
  - inverse is different and slightly more expensive
  - key schedule has some symmetry, but much less

Rijndael implementation aspects

- Implementations can exploit symmetry

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Rijndael implementation aspects

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- Software with table-lookups:
  - 4 Kbytes of table
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- Software with table-lookups:
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- Software in bitslice:
  - rearrangement of the bits
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- Hardware:
  - very suitable thanks to arithmetic in GF(2^n) instead of $(\mathbb{Z}_{2^n}, +)$
  - fully parallel: combinatorial logic with full round
  - serial: logic for 1 S-box and 1 MixColumns matrix column
  - S-box area/circuit depth trade-off by using tower fields

Rijndael security status

- Cryptanalysis (in public domain)
  - all attacks, also on reduced-round, have huge data complexity
  - there is an (academic) attack against full-round AES:
    - biclique attacks [Bogdanov, Khovratovich, Rechberger, 2011]
    - $|Q_c| \approx 2^{126}$: factor 2 gain compared to exhaustive key search
    - gain evaporates when looking at complete picture
  - solid security status thanks to public scrutiny
- Implementation attacks: exploiting implementation weaknesses
  - timing attacks: cache misses in table-lookups
  - power analysis: exploiting dependence of current on data
  - electromagnetic analysis: same for EM emanations
  - fault attacks: exploiting forced faults
- Implementation attacks are the ones that matter in practice!

Currently we are here...

Introduction

Block cipher model and security definition

Data Encryption Standard (DES)

Advanced Encryption Standard (AES)

Encryption modes of block ciphers

Authentication modes of block ciphers

Block cipher modes for encryption

- DES can encipher 8-byte messages, AES of 16-byte messages
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- Stream encryption modes
  - build a stream cipher with a block cipher as building block

Block encryption modes

- Ideal: wide block encryption
  - each cryptogram bit depends on each message bit and vice versa
  - hard to build using a fixed-length block cipher
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- Due to padding, cryptogram is longer than message

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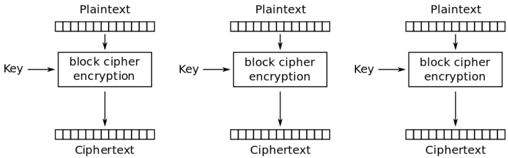
Electronic CodeBook Mode (ECB)



Electronic Codebook (ECB) mode encryption

- Advantages
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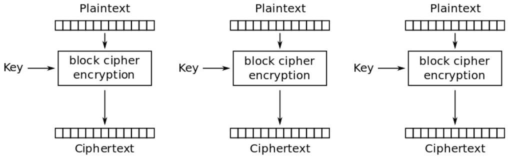
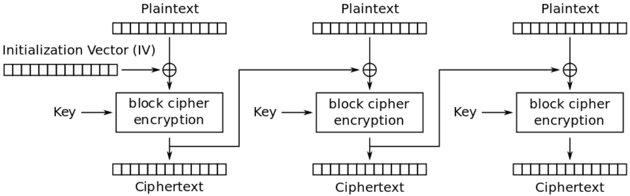


Electronic Codebook (ECB) mode encryption

- Advantages
  - simple
  - parallelizable
- Limitation: equal plaintext blocks $\rightarrow$ equal ciphertext blocks:
  - likely to happen in low-entropy messages
  - problem in padded last block

Cipher Block Chaining mode (CBC)



Cipher Block Chaining (CBC) mode encryption

- *ECB with plaintext block randomized by previous ciphertext block*

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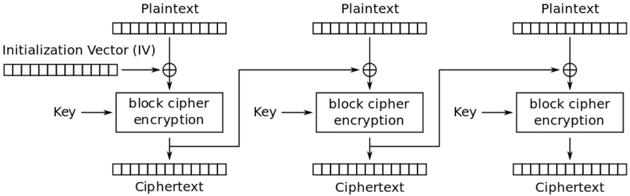

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- *ECB with plaintext block randomized by previous ciphertext block*
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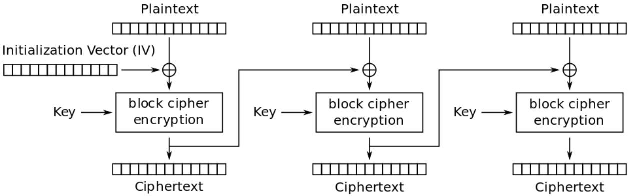

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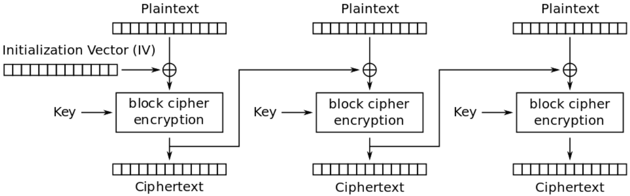

Cipher Block Chaining (CBC) mode encryption

- *ECB with plaintext block randomized by previous ciphertext block*
- First plaintext block randomized with Initial Value (*IV*)
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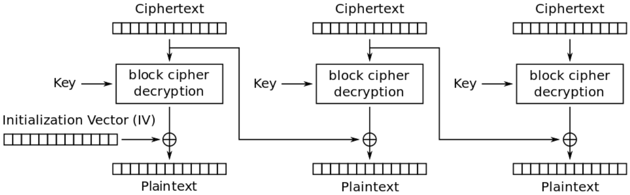
  - requires randomly generating and transferring *IV*

Cipher Block Chaining mode (cont'd)



Cipher Block Chaining (CBC) mode decryption

- Replacing IV randomness by N nonce requirement: $IV = B[K](N)$

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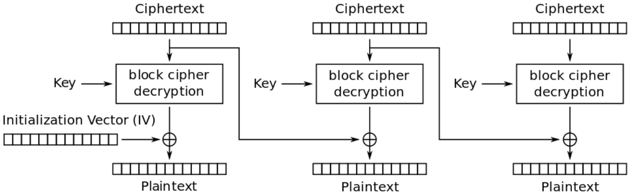
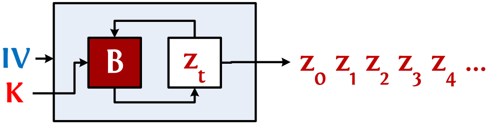


Cipher Block Chaining (CBC) mode decryption

- Replacing IV randomness by N nonce requirement: $IV = B[K](N)$
- Properties of CBC
  - encryption strictly serial, decryption can be parallel
  - IV must be managed and transferred
  - security less than what one would think

Stream encryption: Output FeedBack mode (OFB)



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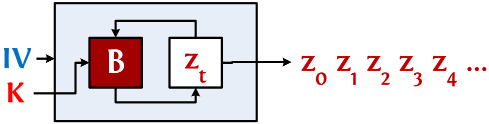

- Stream cipher with:
  - State a^t consisting of two parts: fixed key K and output z_t
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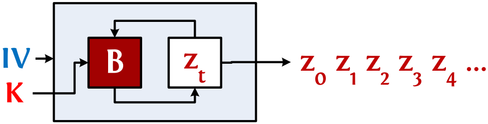

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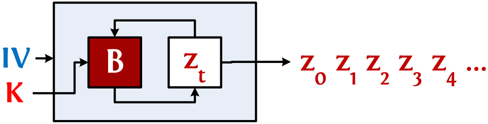

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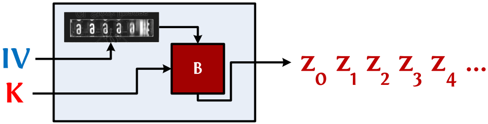
- Properties
  - strictly serial
  - cycle lengths not known in advance
  - no need for B^{-1} (valid for all stream encryption)

Stream encryption: Counter mode



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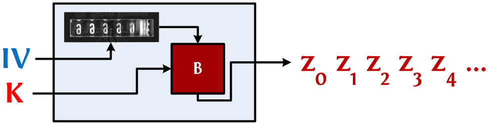

- Stream cipher with:
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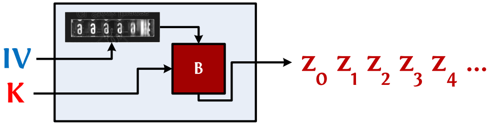

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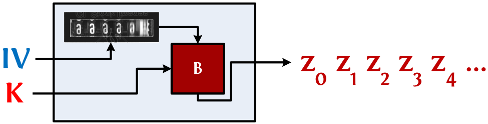

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- Properties
  - fully parallelizable
  - cycle length 2^b with b the block length

Encryption modes: overview

	ECB	CBC	OFB	Counter
parallel encryption	y	n	n	y
parallel decryption	y	y	n	y
random access	y	y	n	y
requires B^{-1}	y	y	n	n
requires padding	y	y	n	n
full collapse if nonce violation	n	n	y	y
error propagation $C \to P$	y	y	n	n

Legend:

- random access: fast decryption of bits anywhere in the message
- error propagation: single-bit error in C expands to b bits in P

Currently we are here...

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Advanced Encryption Standard (AES)

Encryption modes of block ciphers

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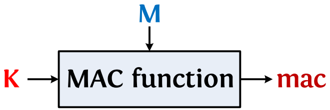
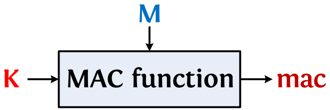
Message authentication code (MAC) functions



Message authentication code (MAC) functions



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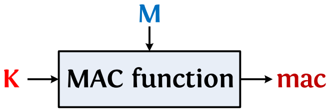

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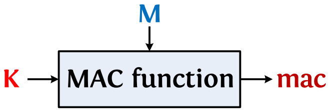

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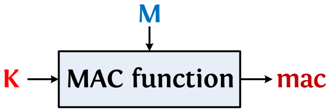

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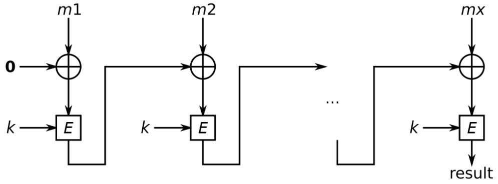
  - returns fully uncorrelated responses for different inuts
- If ideal, Pr(success) of forging a pair $M, T = \mathrm{MAC}(K, M)$ is $2^{-\ell}$

Cipher Block Chaining MAC mode (CBC-MAC)



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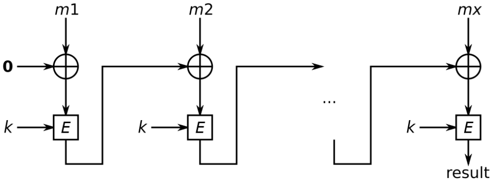
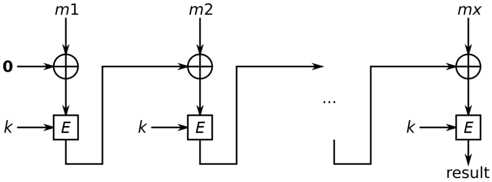


- Observation: in CBC encryption Ci depends on $m1$ to mi

Cipher Block Chaining MAC mode (CBC-MAC)



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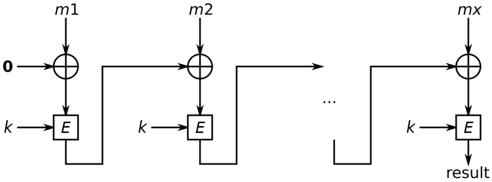

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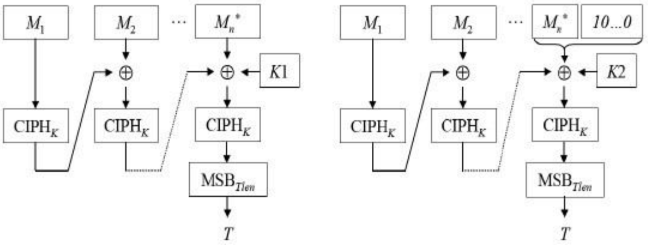
  - length-extension weakness

A fix of CBC-MAC: C-MAC



- NIST standard: Special Publication 800-38B

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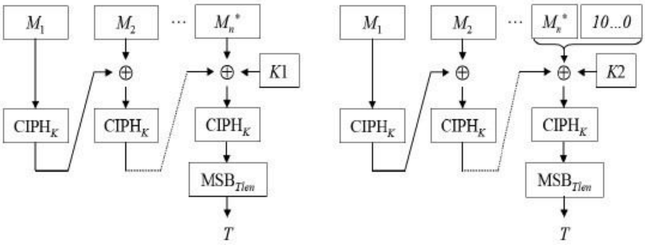

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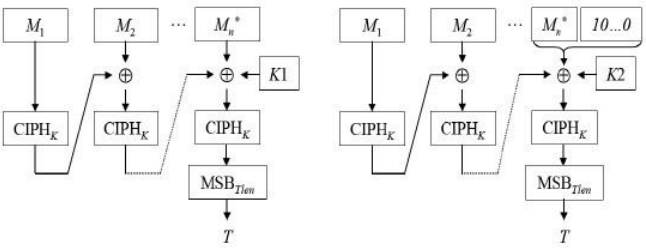

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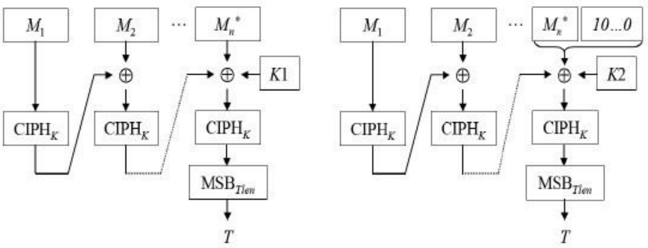

- NIST standard: Special Publication 800-38B
- avoid length-extension by *doing something different at the end*
- addition of a constant before last application of $B[K]$
- Secure for arbitrary-length messages

Currently we are here...

Introduction

Block cipher model and security definition

Data Encryption Standard (DES)

Advanced Encryption Standard (AES)

Encryption modes of block ciphers

Authentication modes of block ciphers

Summary

- Block ciphers are keyed b-bit permutations
  - a different permutation $B[K]$ per key K (and tweak w)
  - with an efficient inverse $B[K]^{-1}$
  - exhaustive keysearch should be best attack (complexity $2^{|K|-1}$)
- DES and AES are the most widespread block ciphers
  - constructed by iterating a simple round function
  - round has steps for non-linearity, mixing and transposition
- Block ciphers are versatile:
  - block encryption modes: e.g., ECB and CBC
  - stream encryption modes: e.g., OFB, counter and CFB
  - MAC computation modes: e.g., CBC-MAC and C-MAC
- Inverse permutation only used in block encryption modes