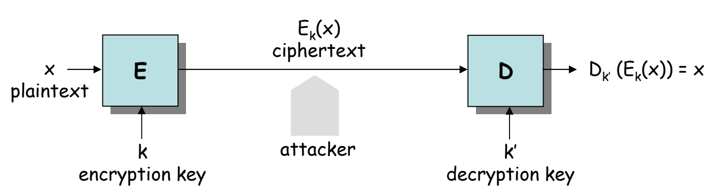
"The best system is to use a simple, well understood algorithm which relies on the security of a key rather than the algorithm itself. This means if anybody steals a key, you could just roll another and they have to start all over."
-- Andrew Carol

Symmetric key cryptography

- preliminaries (operational and attacker models)
- block ciphers (basics, DES, 3DES, AES)
- block ciphers in practice (modes of operation)
- a security flaw induced by CBC padding
- stream ciphers

Operational model of encryption



- attacker's goal:
  - to systematically recover plaintext from ciphertext
  - to deduce the (decryption) key
- Kerckhoff's assumption:
  - attacker knows all details of E and D
  - attacker doesn't know the (decryption) key

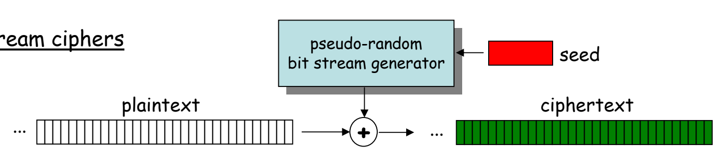
Attack models

- ciphertext-only
  - only data transmitted over the ciphertext channel is available to the attacker
- known-plaintext
  - plaintext-ciphertext pairs are available to the attacker
- chosen-plaintext
  - ciphertexts are available corresponding to plaintexts of the attacker's choice
  - adaptive: choice of plaintexts may depend on previously obtained plaintext-ciphertext pairs
- chosen-ciphertext
  - plaintext-ciphertext pairs are available for some number of ciphertexts of the attacker's choice
  - adaptive: choice of ciphertexts may depend on previously obtained plaintext-ciphertext pairs
- related-key attack
  - attacker has access to the encryption of plaintexts under both the unknown key and keys known to have certain relationship with the unknown key

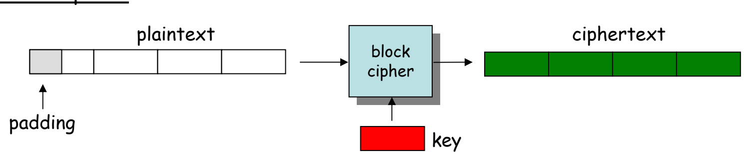
Asymmetric- vs. symmetric-key encryption

- asymmetric-key encryption
  - it is hard (computationally infeasible) to compute k' from k
  - k can be made public (public-key cryptography)
- symmetric-key encryption
  - it is easy to compute k from k' (and vice versa)
  - often k = k'
  - two main types: stream ciphers and block ciphers

<u>stream ciphers</u>



<u>block ciphers</u>



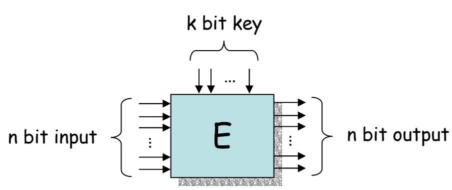
“Feistel and Coppersmith rule: Sixteen rounds and one hell of an avalanche.”
-- Stephan Eisvogel in de.comp.security

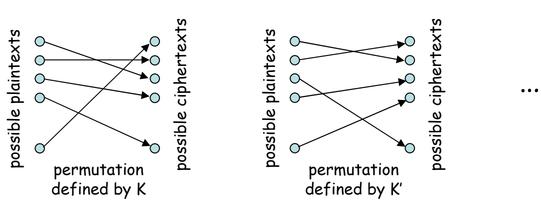
Block ciphers: DES, 3DES, and AES

- basics
- operation of DES
- cryptanalysis of DES
- multiple encryption and the 3DES
- AES

Block ciphers

- an *n* bit block cipher is a function $E: \{0, 1\}^n \times \{0, 1\}^k \rightarrow \{0, 1\}^n$, such that for each $K \in \{0, 1\}^k$, $E(X, K) = E_K(X)$
  - is an invertible mapping from $\{0, 1\}^n$ to $\{0, 1\}^n$
  - cannot be efficiently distinguished from a random permutation
- the inverse of $E_K(X)$ is denoted by $D_K(Y)$, where $Y = E_K(X)$





Trade-offs in block size

- attacks based on small block size
  - text dictionary attack
    - plaintext-ciphertext pairs become known for a fixed key
    - the "larger" the dictionary the greater the chance of locating a random ciphertext in it
    - if n is small, then it is feasible to build "large" dictionaries
  - matching ciphertext attacks
    - if a dictionary of size about $2^{n/2}$ have been created, and about $2^{n/2}$ ciphertexts are subsequently given, then one expects to locate a ciphertext in the dictionary with high probability (birthday paradox)

→ larger block size is more secure

- disadvantages of large block size
  - more costly to implement (in terms of gates or low level instructions)

Exhaustive key search and key size

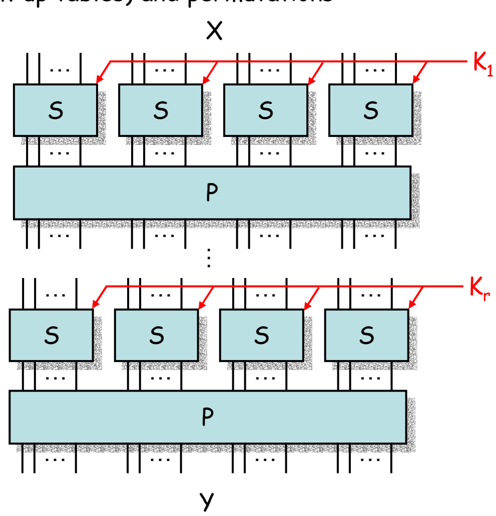
- given a small number of plaintext-ciphertext pairs encrypted under a key K, K can be recovered by exhaustive key search with 2^{k-1} processing complexity (expected number of operations)
  - input: (X, Y), (X', Y'), …
  - progress through the entire key space
    - for each trial key K', decrypt Y
    - if the result is not X, then throw away K'
    - if the result is X, then check the other pairs (X', Y'), …
    - if K' does not work for at least one pair, then throw away K'
  - if K' worked for all pairs (X, Y), (X', Y'), …, then output K' as the target key
  - on average, the target key is found after searching half of the key space
- if the plaintexts are known to contain redundancy, then ciphertext-only exhaustive key search is possible with a relatively small number of ciphertexts

How to build a “strong” block cipher?

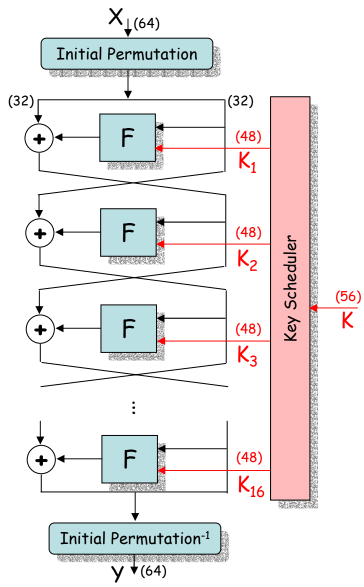
- complex encryption function can be built by composing several simple operations which offer complementary – but individually insufficient – protection
- simple operations:
  - elementary arithmetic operations
  - logical operations (e.g., XOR)
  - modular multiplication
  - transpositions
  - substitutions
  - etc.
- let’s combine two or more transformations in a manner that the resulting cipher is more secure than the individual components

Example: SP networks

- an SP (substitution-permutation) network is a *product cipher* composed of stages each involving key controlled substitutions (non-linear look-up tables) and permutations

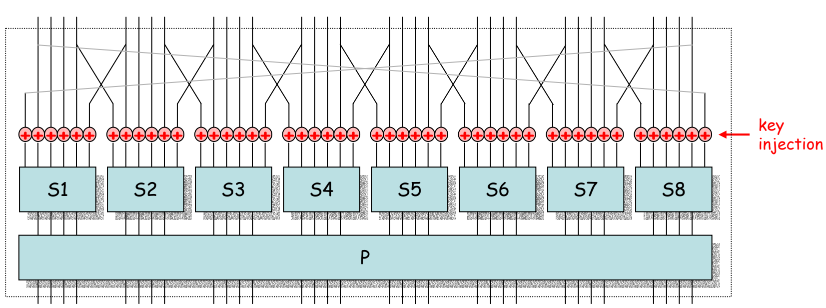


DES – Data Encryption Standard



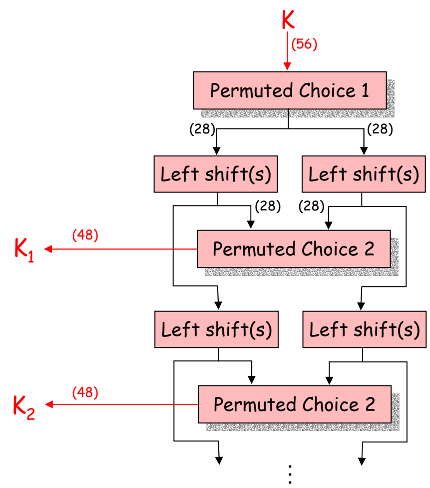
- input size: 64
- output size: 64
- key size: 56
- 16 rounds
- Feistel structure

DES round function F



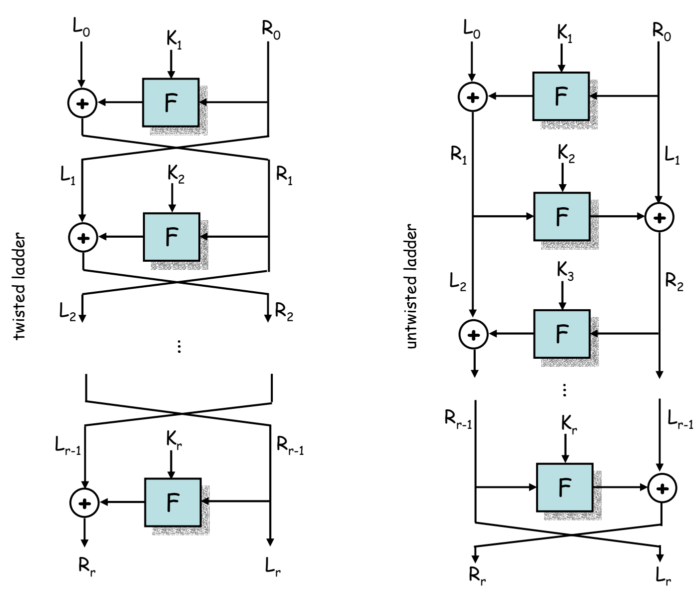
- Si – substitution box (S-box)
- P – permutation box (P-box)

DES key scheduler



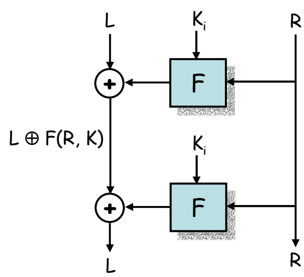
- each key bit is used in around 14 out of 16 rounds

Feistel structure illustrated



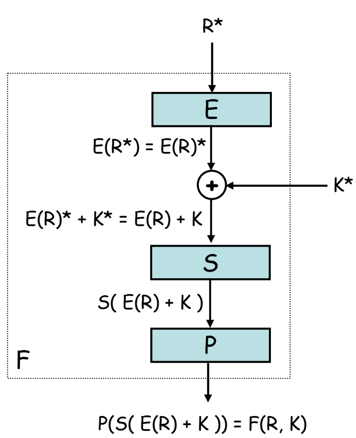
Properties of Feistel ciphers

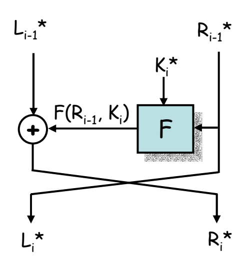
- round i maps (L_{i-1}, R_{i-1}) into (L_i, R_i) as follows:
  $L_i = R_{i-1}$
  $R_i = L_{i-1} \oplus F(R_{i-1}, K_i)$
- a Feistel cipher is always invertible even if F is not invertible:
  $R_{i-1} = L_i$
  $L_{i-1} = R_i \oplus F(R_{i-1}, K_i) = R_i \oplus F(L_i, K_i)$
- decryption can be achieved using the same r-round process with the round keys used in reverse order (K_r through K_1)



Complementation property of DES

- $Y = DES_K(X)$ implies $Y^* = DES_{K^*}(X^*)$
  - where X^* denotes the bitwise complement of X





Consequences of the complementation prop.

- assume an attacker can mount a chosen-plaintext attack
- the attacker chooses a plaintext X, and obtains $Y_1 = DES_K(X)$ and $Y_2 = DES_K(X^*)$
- by the complementation property, the attacker knows that $DES_{K^*}(X) = Y_2^*$
- the attacker then runs an exhaustive key search
  - for each trial key K', he computes $Y' = DES_{K'}(X)$
    - if $Y' = Y_1$, then K' is possibly the target key (should be further tested)
    - if $Y' = Y_2^*$, then K'* is possibly the target key (should be further tested)
    - otherwise throw away **both** K' and K'*
- expected number of keys required before success is reduced from 2^{55} to 2^{54}
- still impractical as an attack

DES weak keys and semi-weak keys

- a weak key is a key K such that $DES_K(DES_K(X)) = X$
  - there are 4 DES weak keys:

```
0101 0101 0101 0101
FEFE FEFE FEFE FEFE
1F1F 1F1F 0E0E 0E0E
E0E0 E0E0 F1F1 F1F1
```

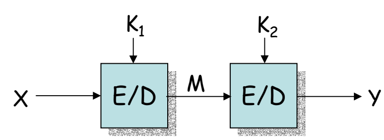
- a semi-weak key pair is a pair (K_1, K_2) such that $DES_{K_1}(DES_{K_2}(X)) = X$
  - there are 6 pairs of DES semi-weak keys
- why are these keys weak?
  - for each weak key K, there exist 2^{32} fix points of DES_K, i.e., plaintext X such that $DES_K(X) = X$
  - for 4 out of the 12 semi-weak keys, there exist 2^{32} anti-fix points, i.e., plaintext X such that $DES_K(X) = X^*$

Linear and differential cryptanalysis of DES

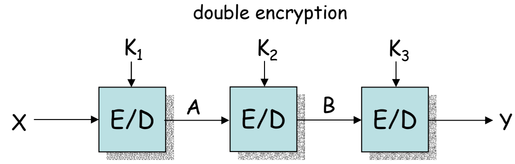
- linear cryptanalysis (LC)
  - linear cryptanalysis is the most powerful attack against DES to date
  - requires an enormous number ($\sim 2^{43}$) known plaintext-ciphertext pairs → infeasible in practical environments
  - could work in a ciphertext only model if plaintexts are redundant (e.g., contain parity bits)
- differential cryptanalysis (DC)
  - most general cryptanalytic tool to date against iterated block ciphers (including DES, FEAL, IDEA)
  - primarily a chosen-plaintext attack
  - in case of DES, it requires $\sim 2^{47}$ chosen plaintext-ciphertext pairs → infeasible in practical environments
- DES was optimized against DC when it was designed
- it can, however, be improved with respect to LC (apparently the designers of DES was not aware of this attack at that time)

Multiple encryption and 3DES

- if a block cipher is susceptible to exhaustive key search (e.g., DES), then encryption of the same message more than once may increase security



double encryption



triple encryption

  - stage keys may not be independent
    - e.g., two-key 3DES: $K_1 = K_3$
  - a stage cipher may be either a block cipher or its corresponding decryption function
    - e.g., 3DES-EDE (encryption-decryption-encryption)

Meet-in-the-middle attack on double enc.

- a naïve exhaustive key search attack on double encryption tries all 2^{2k} keys
- a known-plaintext meet-in-the-middle attack defeats double encryption using an order of 2^k operations and 2^k storage
  - attack time is reduced at the cost of substantial space
- meet-in-the-middle attack:
  - input: known plaintext-ciphertext pairs (X, Y), (X', Y'), …
  - compute $M_i = E_i(X)$ for all possible key values $K_1 = i$ and store all (M_i, i) pairs in a table
  - compute $M'_j = D_j(Y)$ for all possible key values $K_2 = j$ and check for hits $M'_j = M_i$ against entries in the stored table
    - M'j need not be stored, it can be checked as it is generated
  - each hit identifies a candidate solution key pair (i, j)
  - using a second plaintext-ciphertext pair (X', Y'), discard false hits
  - for an L stage cascade of random ciphers, the expected number of false key hits when t plaintext-ciphertext pairs are available is 2^{Lk-tn}, where n and k are the block and key sizes, resp.

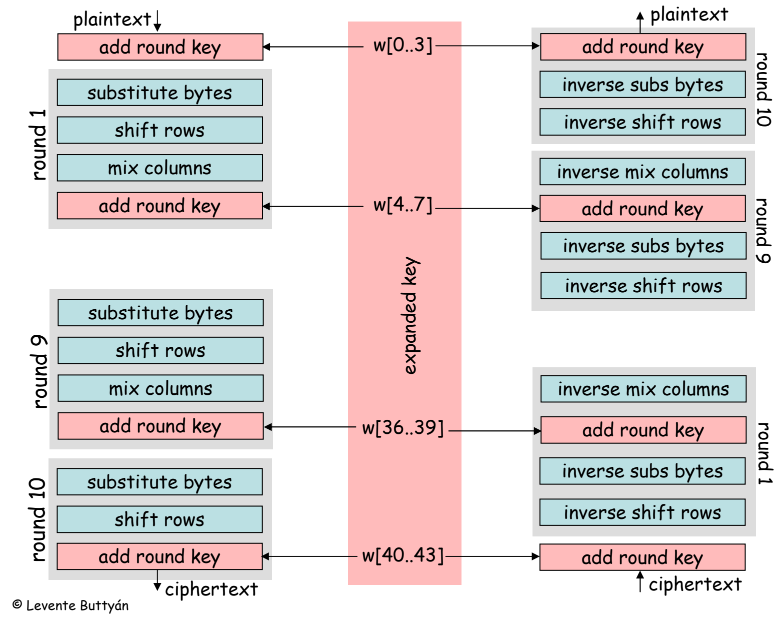
AES – Advanced Encryption Standard

- NIST selected Rijndael (designed by Joan Daemen and Vincent Rijmen) as a successor of DES (3DES) in November 2001
- Rijndael parameters

key size	128	192	256
input/output size	128	128	128
number of rounds	10	12	14
round key size	128	128	128

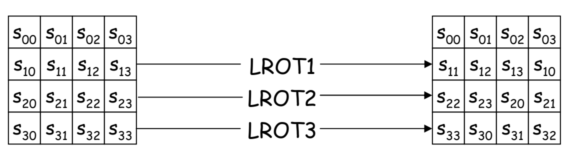
- not Feistel structure
- decryption algorithm is different from encryption algorithm (optimized for encryption)
- single 8 bit to 8 bit S-box
- key injection (bitwise XOR)

General structure of encryption/decryption

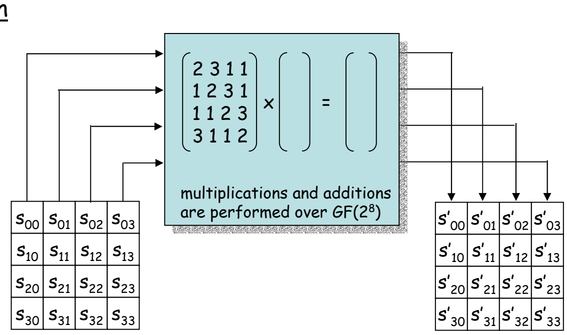


Shift row and mix column

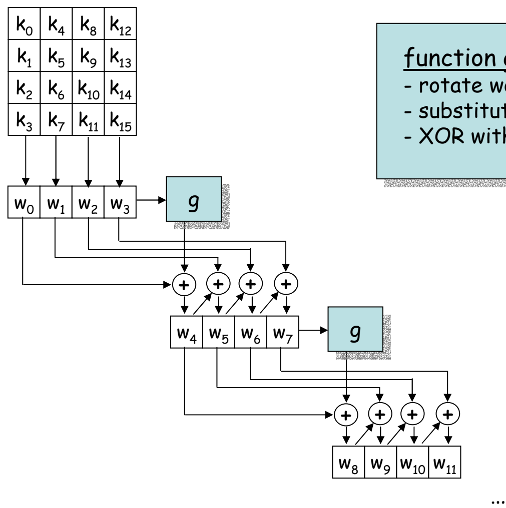
shift row



mix column



Key expansion



function g
- rotate word
- substitute bytes
- XOR with round constant

Summary

- block cipher basics
  - trade-offs in block size
  - trade-offs in key size, exhaustive key search
  - product ciphers, SP networks
- DES
  - operation
  - properties (Feistel structure, complementation, weak keys)
  - differential and linear cryptanalysis
  - multiple encryption and the 3DES
  - meet-in-the middle attack on 2DES
- AES
  - operation

Using a block cipher in practice: modes of operation

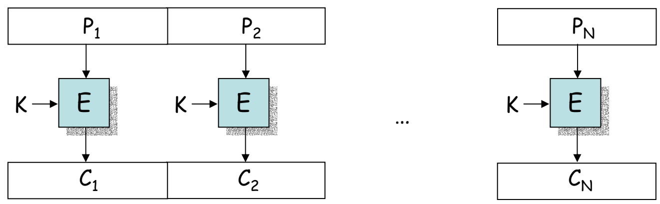
- ECB
- CBC
- CFB, OFB, CTR

Block cipher modes of operation

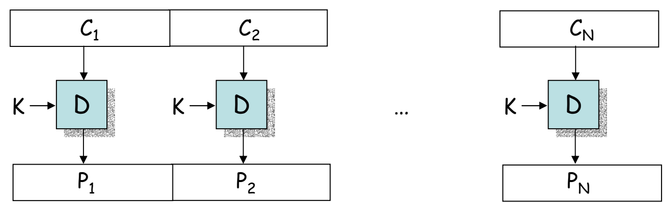
- ECB – Electronic Codebook
  - used to encipher a single plaintext block (e.g., a DES key)
- CBC – Cipher Block Chaining
  - repeated use of the encryption algorithm to encipher a message consisting of many blocks
- CFB – Cipher Feedback
  - used to encipher a stream of characters, dealing with each character as it comes
- OFB – Output Feedback
  - another method of stream encryption, used on noisy channels
- CTR – Counter
  - simplified OFB with certain advantages
- triple-inner-CBC and triple-outer-CBC
  - possible modes of operation when multiple encryption is used

ECB mode

- encrypt



- decrypt



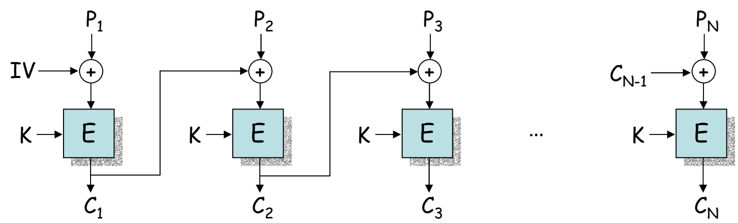
Properties of ECB mode

- identical plaintext blocks result in identical ciphertext blocks (under the same key of course)
  - messages to be encrypted often have very regular formats
  - repeating fragments, special headers, string of 0s, etc. are quite common
- blocks are encrypted independently of other blocks
  - reordering ciphertext blocks result in correspondingly reordered plaintext blocks
  - ciphertext blocks can be cut from one message and pasted in another, possibly without detection
- error propagation: one bit error in a ciphertext block affects only the corresponding plaintext block (results in garbage)

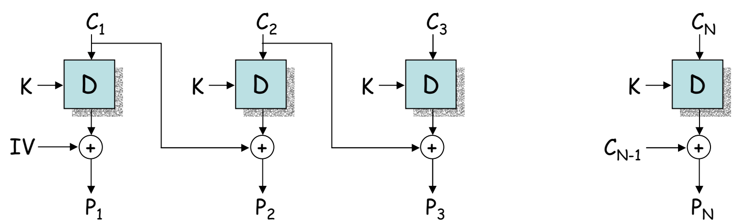
- overall: not recommended for messages longer than one block, or if keys are reused for more than one block

CBC mode

- encrypt



- decrypt



Properties of CBC mode

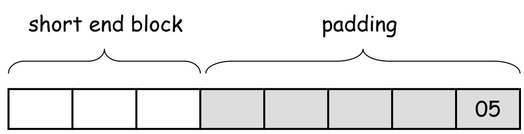
- encrypting the same plaintexts under the same key, but different IVs result in different ciphertexts
- ciphertext block C_j depends on P_j and all preceding plaintext blocks
  - rearranging ciphertext blocks affects decryption
  - however, dependency on the preceding plaintext blocks is only via the previous ciphertext block C_{j-1}
  - proper decryption of a correct ciphertext block needs a correct preceding ciphertext block only
- error propagation:
  - one bit error in a ciphertext block C_j has an effect on the j-th and (j+1)-st plaintext block
    - P_j' is complete garbage and P_{j+1}' has bit errors where C_j had
    - an attacker may cause predictable bit changes in the (j+1)-st plaintext block
- error recovery:
  - recovers from bit errors (self-synchronizing)
  - cannot, however, recover from frame errors ("lost" bits)

Integrity of the IV in CBC mode

- the IV need not be secret, but its integrity should be protected
  - malicious modification of the IV allows an attacker to make predictable changes to the first plaintext block recovered
- one solution is to send the IV in an encrypted form at the beginning of the CBC encrypted message

Padding

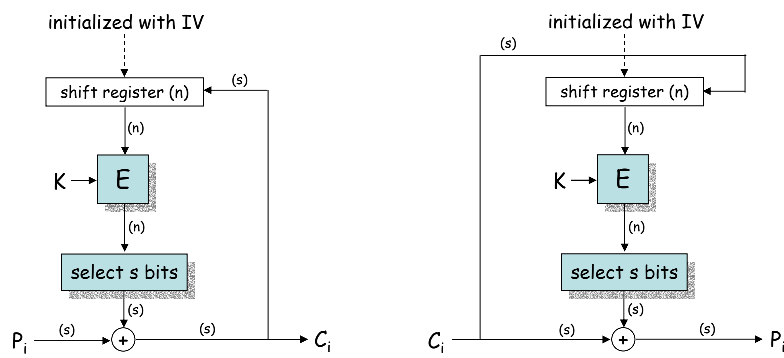
- the length of the message may not be a multiple of the block size of the cipher
- one can add some extra bytes to the short end block until it reaches the correct size – this is called padding
- usually the last byte indicates the number of padding bytes added – this allows the receiver to remove the padding



- note: if the encrypted message must have the same size as the clear message, then no padding can be used
  - encrypt the last ciphertext block again
  - select m bits and XOR them to the remaining m bits of the clear message

CFB mode

- encrypt
- decrypt

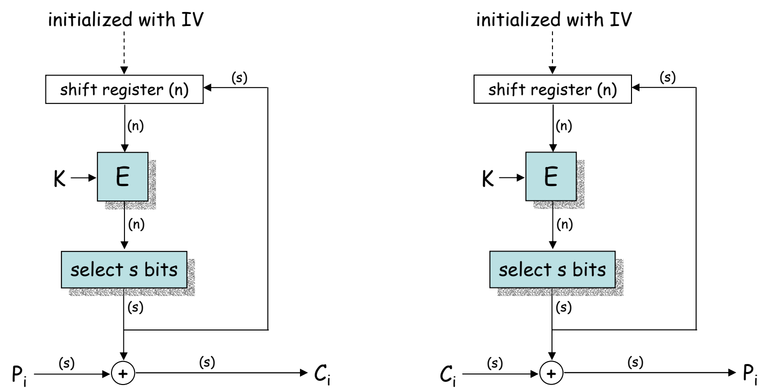


Properties of CFB mode

- encrypting the same plaintexts under the same key, but different IVs result in different ciphertexts
- the IV can be sent in clear
- ciphertext block C_j depends on P_j and all preceding plaintext blocks
  - rearranging ciphertext blocks affects decryption
  - proper decryption of a correct ciphertext block needs the preceding n/s ciphertext blocks to be correct
- error propagation:
  - one bit error in a ciphertext block C_j has an effect on the decryption of that and the next n/s ciphertext blocks (the error remains in the shift register for n/s steps)
    - P_j' has bit errors where C_j had, all the other erroneous plaintext blocks are garbage
    - an attacker may cause predictable bit changes in the j-th plaintext block
- error recovery:
  - self synchronizing, but requires n/s blocks to recover

OFB mode

- encrypt
- decrypt

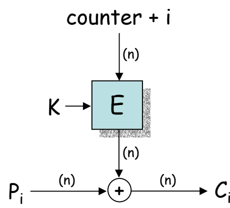


Properties of OFB mode

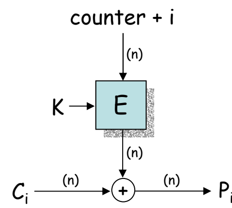
- a different IV should be used for every new message, otherwise messages will be encrypted with the same key stream
- the IV can be sent in clear
  - however, if the IV is modified by the attacker, then the cipher will never recover (unlike CFB)
- ciphertext block C_j depends on P_j only (does not depend on the preceding plaintext blocks)
  - however, rearranging ciphertext blocks affects decryption
- feedback size should be equal to n
  - (= n) → cycle length is around 2^{n-1}
  - (< n) → cycle length is around $2^{n/2}$
- error propagation:
  - one bit error in a ciphertext block C_j has an effect on the decryption of <u>only that ciphertext block</u>
    - P_j' has bit errors where C_j had
    - an attacker may cause predictable bit changes in the j-th plaintext block
- error recovery:
  - recovers from bit errors
  - never recovers if bits are lost or the IV is modified

CTR mode

- encrypt



- decrypt



Properties of CTR mode

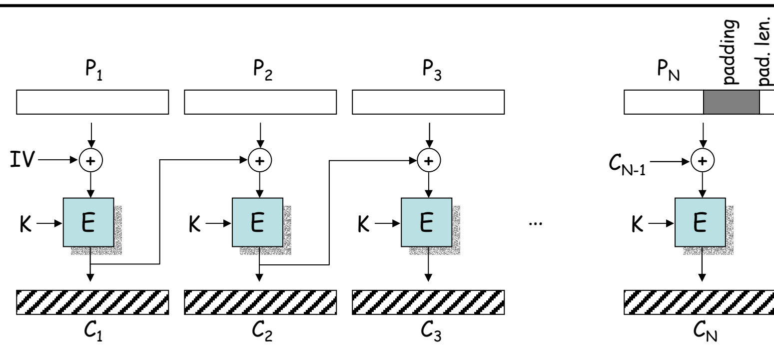
- similar to OFB
- cycle length depends on the size of the counter (typically 2^n)
- the i-th block can be decrypted independently of the others
  - parallelizable (unlike OFB)
  - random access
- the values to be XORed with the plaintext can be pre-computed
- at least as secure as the other modes

note1: in CFB, OFB, and CTR mode only the encryption algorithm is used (decryption is not needed)
  - that is why Rijndael is optimized for encryption
  - these modes shouldn't be used with public-key encryption algs.

note2: the OFB and CTR modes essentially make a synchronous stream cipher out of a block cipher, whereas the CFB mode converts a block cipher into a self-synchronizing stream-cipher

A security flaw induced by CBC padding

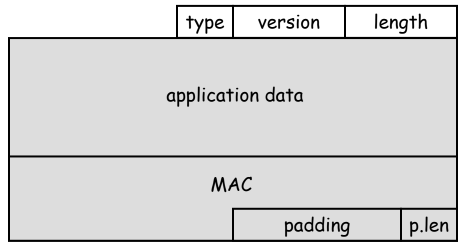
CBC encryption with padding



- TLS padding
  - last byte is the length n of the padding
  - all padding bytes have the value n
  - examples for correct padding: 0, 11, 222, 3333, …
- verification of TLS padding:
  - if the last byte is n, then verify if the last n+1 bytes are all n

Side channel

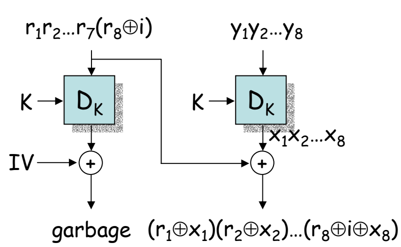
- TLS record message format



- send a random message to a TLS server
- the server will drop the message with overwhelming probability
  - either the padding is incorrect (the server responds with a DECRYPTION_FAILED alert)
  - or the MAC is incorrect with very high probability (the server responds with BAD_RECORD_MAC alert)
- if the response is BAD_RECORD_MAC, then the padding was correct
  → we get 1 bit of information !

Last byte(s) oracle

- assume we have an encrypted block $y_1y_2...y_8 = E_K(x_1x_2...x_8)$
- we want to compute x_8 (the last byte of x)
- idea:
  1. choose a random block $r_1r_2...r_8$; let i = 0
  2. send $r_1r_2...r_7(r_8 \oplus i)y_1y_2...y_8$ to the server (oracle)
  3. if there's a padding error, then increment i and go back to step 2
  4. if there's no padding error, then $r \oplus x$ ends with 0 or 11 or 222 …
     - the most likely is that $(r_8 \oplus i) \oplus x_8 = 0$, and hence $x_8 = r_8 \oplus i$



Last byte(s) oracle

- assume we get that $x \oplus r$ has a correct padding, but we don't know if it is 0 or 11 or 222 …
- idea:
  1. let j = 1
  2. change r_j and send $r_1 r_2 \ldots r_8 y_1 y_2 \ldots y_8$ to the server again
  3. if the padding is still correct then the j-th byte was not a padding byte; increment j and go back to step 2
  4. if the padding becomes incorrect then the j-th byte was the first padding byte; $x_j \oplus r_j | x_{j+1} \oplus r_{j+1} | \ldots | x_8 \oplus r_8 = (8-j) | \ldots | (8-j)$ and hence $x_j\, x_{j+1} \ldots x_8 = r_j \oplus (8-j)\; r_{j+1} \oplus (8-j) \ldots r_8 \oplus (8-j)$

```
x = DE AD BE EF DE AD BE EF
r = 01 23 45 67 DD AE BD EC
r⊕x = DF 8E FB 88 03 03 03 03
```

j	r	r⊕x	padding
1	00 23 45 67 DD AE BD EC	DE 8E FB 88 03 03 03 03	OK
2	00 22 45 67 DD AE BD EC	DE 8F FB 88 03 03 03 03	OK
3	00 22 44 67 DD AE BD EC	DE 8F FA 88 03 03 03 03	OK
4	00 22 44 66 DD AE BD EC	DE 8F FA 89 03 03 03 03	OK
5	00 22 44 66 DC AE BD EC	DE 8F FA 89 02 03 03 03	ERROR

$x_5\, x_6\, x_7\, x_8$ = DD⊕03 AE⊕03 BD⊕03 EC⊕03 = DE AD BE EF

Block decryption oracle

- assume we have an encrypted block $y_1 y_2 \ldots y_8 = E_K(x_1 x_2 \ldots x_8)$ and we know the value of $x_j x_{j+1} \ldots x_8$ (using the last byte(s) oracle)
- we want to compute x_{j-1}
- idea:
  1. choose a random block $r_1 r_2 \ldots r_8$ such that $r_j = x_j \oplus (9-j)$; $r_{j+1} = x_{j+1} \oplus (9-j)$; … $r_8 = x_8 \oplus (9-j)$;
  2. let i = 0
  3. send $r_1 r_2 \ldots r_{j-2} (r_{j-1} \oplus i) r_j \ldots r_8 y_1 y_2 \ldots y_8$ to the server (oracle)
  4. if there's a padding error then increment i and go back to step 3
  5. if there's no padding error then $x_{j-1} \oplus r_{j-1} \oplus i = 9-j$ and hence $x_{j-1} = r_{j-1} \oplus i \oplus (9-j)$

```
x = DE AD BE EF DE AD BE EF
r = 01 23 45 67 DA A9 BA EB
r⊕x = DF 8E FB 88 04 04 04 04
```

i	r	r⊕x	padding
0	01 23 45 67 DA A9 BA EB	DF 8E FB 88 04 04 04 04	ERROR
1	01 23 45 66 DA A9 BA EB	DF 8E FB 89 04 04 04 04	ERROR
…	…	…	…
140	01 23 45 EB DA A9 BA EB	DF 8E FB 04 04 04 04 04	OK

x_4 = 67⊕8C⊕04 = EF

Decryption oracle

- assume we have a CBC encrypted message (C_1, C_2, …, C_N) where
  - $C_1 = E_K(P_1 \oplus IV)$
  - $C_i = E_K(P_i \oplus C_{i-1})$ (for $1 < i < N$)
  - $C_N = E_K([P_N|pad|plen] \oplus C_{N-1})$
- we want to compute P_1, P_2, … P_N
- idea:
  - decrypt C_N using the block decryption oracle and XOR the result to C_{N-1}; you get P_N|pad|plen
  - decrypt C_i using the block decryption oracle and XOR the result to C_{i-1}; you get P_i
  - decrypt C_1 using the block decryption oracle and XOR the result to IV; you get P_1 (if IV is secret you cannot get P_1)

complexity of the whole attack:

on average we need only $\frac{1}{2}$*256*8*N = 1024*N oracle calls !

A security flaw induced by CBC padding

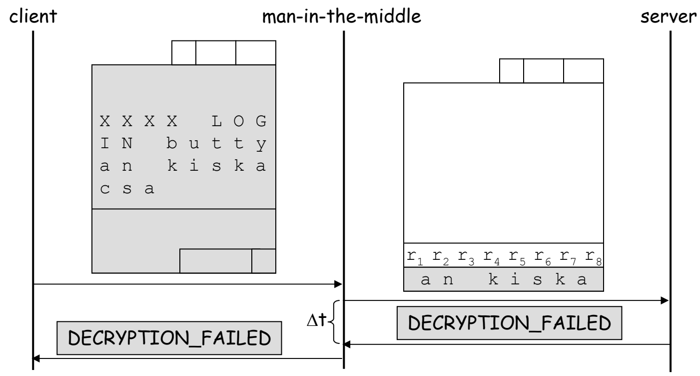
Application

- vulnerable protocols: SSL, TLS, WTLS, IPsec, …
- some notes:
  - problems (and solutions) with TLS
    - alert messages are encrypted → BAD_RECORD_MAC and DECRYPTION_FAILED cannot be distinguished
      - measure timing between oracle call and oracle response
      - BAD_RECORD_MAC takes more time than DECRYPTION_FAILED
    - BAD_RECORD_MAC and DECRYPTION_FAILED are fatal errors → connection is closed after one oracle call
      - a password can still be broken if it is sent periodically to a server using TLS (a different session is used each time the password is sent)

A security flaw induced by CBC padding

Example: IMAP over TLS

- Outlook Express checks for new mail on the server periodically (every 5 minutes)
- each time the same password is sent for every folder
  XXXX LOGIN "username" "password"<0D><0A>
- it is possible to uncover the password using the attack as follows:



Fixes

- randomize response time after an error occurred (measuring timing of alert messages won't work)
- use random padding bytes
- put the padding before the MAC !

Stream ciphers

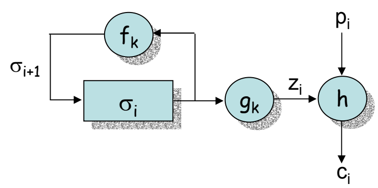
- general principles
- one-time pad
- LFSR based stream ciphers
- RC4

General principles

- while block ciphers simultaneously encrypt groups of characters, stream ciphers encrypt individual characters
  - may be better suited for real time applications
- stream ciphers are usually faster than block ciphers in hardware (but not necessarily in software)
- limited or no error propagation
  - may be advantageous when transmission errors are probable

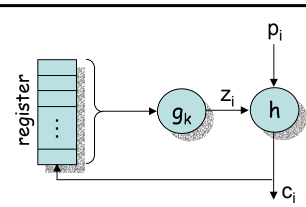
- note: the distinction between stream ciphers and block ciphers is not definitive
  - stream ciphers can be built out of block ciphers using CFB, OFB, or CTR modes
  - a block cipher in ECB or CBC mode can be viewed as a stream cipher that operates on large characters

Synchronous stream ciphers



- the key stream is generated independently of the plaintext and of the ciphertext
- properties:
  - needs synchronization between the sender and the receiver
    - if a character is inserted into or deleted from the ciphertext stream then synchronization is lost and the plaintext cannot be recovered
    - additional techniques must be used to recover from loss of synch.
    - → insertion and deletion are easy to detect by the receiver
  - no error propagation
    - a ciphertext character that is modified during transmission affects only the decryption of that character
    - → an attacker can make changes to selected ciphertext characters and know exactly what effect these changes have on the plaintext (if h = XOR)

Self-synchronizing stream ciphers



- the key stream is generated as a function of a fixed number of previous ciphertext characters
- properties:
  - self-synchronizing
    - since the size t of the register is fixed, a lost ciphertext character affects only the decryption of the next t ciphertext characters
    - → more difficult to detect insertion and deletion of ciphertext char's
  - limited error propagation
    - if a ciphertext character is modified, then decryption of the next t ciphertext characters may be incorrect
    - → modifications are easier to detect than in case of synch. stream ciphers
  - ciphertext characters depend on all previous plaintext characters
    - better diffusion of plaintext statistics

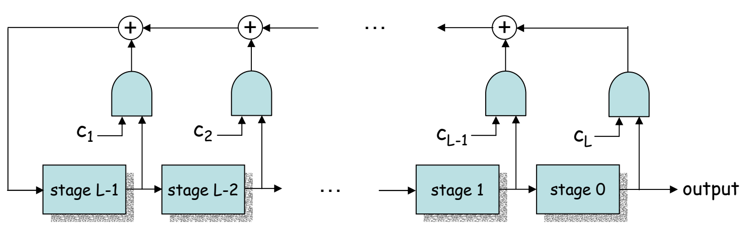
Vernam cipher and the one-time pad

- Vernam cipher
  - $c_i = p_i \oplus k_i$ for i = 1, 2, …
    where p_i are the plaintext digits, k_i are the key stream digits, c_i are the ciphertext digits, and $\oplus$ is the bitwise XOR operation

- one-time pad
  - a Vernam cipher where the key stream digits are generated independently and uniformly at random
  - the one-time pad is unconditionally secure [Shannon, 1949]
    - $I(P; C) = H(P) - H(P|C) = 0$
  - a necessary condition for a symmetric key cipher to be unconditionally secure is that $H(K) \geq H(P)$ [Shannon, 1949]
    - practically, the key must have as many bits as the compressed plaintext
    - impractical because of key management problems

Stream ciphers

Linear feedback shift registers (LFSR)



- where each $c_i \in \{0, 1\}$ and each stage can store 1 bit
- operation is controlled by a clock
- during each time unit
  - the content of stage 0 is output
  - the contents of a fixed subset of stages are XORed
  - the content of stage i is moved to stage i-1 (i = 1, 2, …, L-1) and the result of the XOR operation is moved in stage L-1 (feedback)

Stream ciphers

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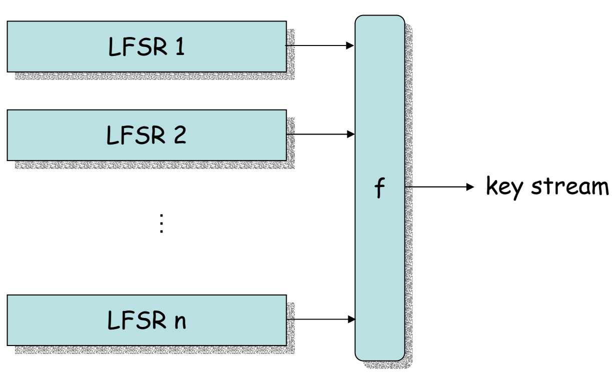
Maximum length LFSR and linear complexity

- maximum length LFSR
  - since the number of possible states of an LFSR is finite, the output stream it produces is always periodic
  - an LFSR is maximum length LFSR, if it produces an output sequence with maximum possible period 2^L-1 (m-sequence)
  - m-sequences have good statistical properties
- linear complexity
  - the linear complexity $L(s^n)$ of a finite binary sequence s^n is the length of the shortest LFSR that generates a sequence having s^n as its first n elements
  - Berlekamp-Massey algorithm:
    - let s be a binary sequence of linear complexity L, and let t be a finite subsequence of s of length at least 2L
    - the Berlekamp-Massey algorithm with input t determines an LFSR of length L that generates s

  → an LFSR should not be used as a key stream generator, as the resulting stream cipher would be vulnerable to known-plaintext attacks

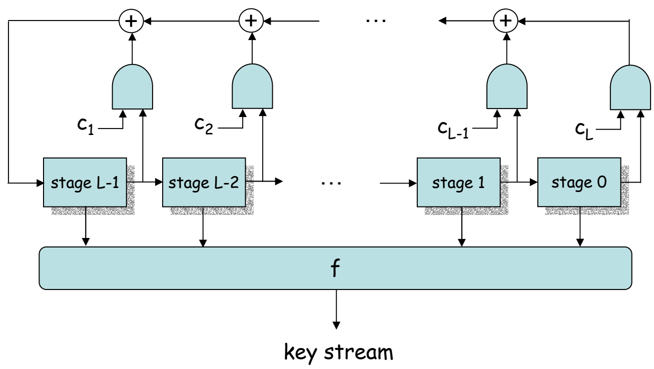
Stream ciphers based on LFSRs

- nonlinear combination generators



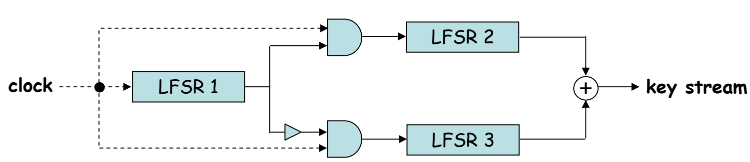
Stream ciphers based on LFSRs

- nonlinear filter generators

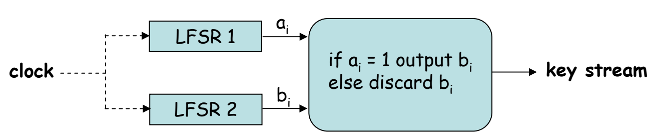


Stream ciphers based on LFSRs

- clock-controlled generators
  - alternating step generator



  - shrinking generator



RC4 stream cipher

- initialization (input: a seed K of keylen bytes)

```
for i = 0 to 255 do
    S[i] = i;
    T[i] = K[i mod keylen];
```

- initial permutation

```
j = 0;
for i = 0 to 255 do
    j = (j + S[i] + T[i]) mod 256;
    swap(S[i], S[j]);
```

- stream generation (output: a stream of pseudo-random bytes)

```
i, j = 0;
while true
    i = (i + 1) mod 256;
    j = (j + S[i]) mod 256;
    swap(S[i], S[j]);
    output S[(S[i] + S[j]) mod 256];
```