CPE 542: CRYPTOGRAPHY & NETWORK SECURITY

Chapter 3: Block Ciphers and the Data Encryption Standard

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Block vs Stream Ciphers

- block ciphers treats messages as blocks to be then en/decrypted separately.
- stream ciphers process messages a bit or byte at a time when en/decrypting—e.g., Vigenere
- many current ciphers are block ciphers- most major network-based cryptographic appliactions

Block Cipher Principles

- most symmetric block ciphers are based on a **Feistel Cipher Structure**
- needed since must be able to **decrypt** ciphertext to recover messages efficiently
- block ciphers look like an extremely large substitution
- would need table of 2^{64} entries for a 64-bit block
- instead create from smaller building blocks
- using idea of a product cipher
- It has complex structure compared to public-key algorithms

Motivation for Feistel Structure

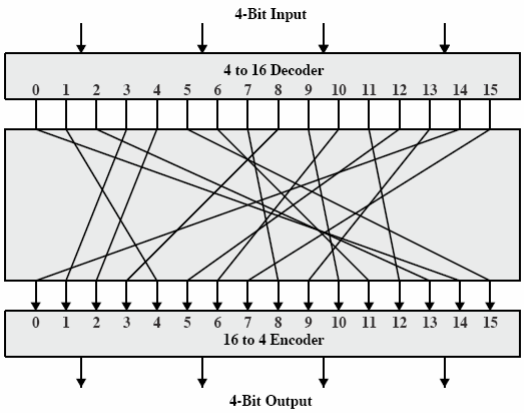


Figure 3.4 General *n*-bit-*n*-bit Block Substitution (shown with $n = 4$)

Claude Shannon and Substitution-Permutation Ciphers

- in 1949 Claude Shannon introduced idea of Substitution-Permutation (S-P) networks
  - modern substitution-transposition product cipher
- these form the basis of modern block ciphers
- S-P networks are based on the two primitive cryptographic operations we have seen before:
  - *substitution* (S-box)
  - *permutation* (P-box)
- provide *confusion* and *diffusion* of message

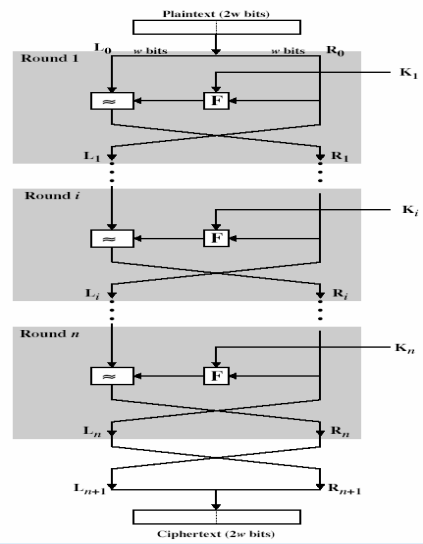
Confusion and Diffusion

- cipher needs to completely obscure statistical properties of original message
- a one-time pad does this
- more practically Shannon suggested combining elements to obtain:
- **diffusion** – dissipates statistical structure of plaintext over bulk of ciphertext (each plaintext bit affect the value of many ciphertext bits)
- **confusion** – makes relationship between ciphertext and key as complex as possible- use complex substitution algorithm

Feistel Cipher Structure

- Horst Feistel proposed the F**eistel cipher**
  - based on concept of invertible product cipher
- partitions input block into two halves
  - process through multiple rounds which
  - perform a substitution on left data half
  - based on round function of right half & subkey
  - then have permutation swapping halves
- implements Shannon's substitution-permutation network concept

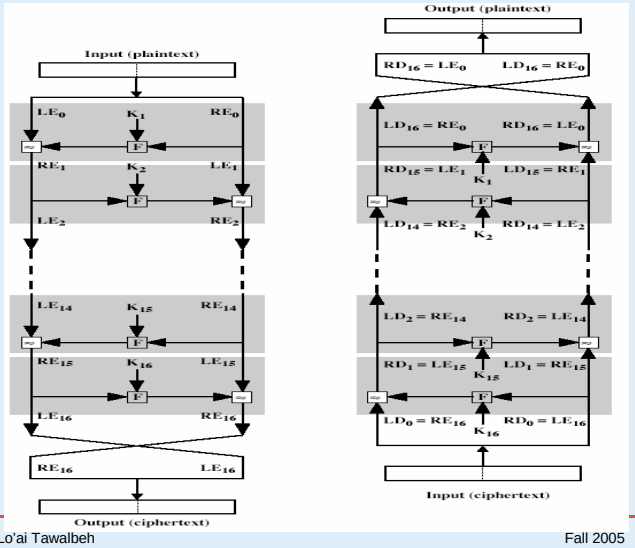
Feistel Cipher Structure



Feistel Cipher Design Principles

- **block size**
  - increasing block provides more security, but reduces the en/decryption speed
- **key size**
  - larger size → greater security, makes exhaustive key searching harder, but may slow cipher (common 64, 128)
- **number of rounds**
  - More rounds → more security. (Typical 16 rounds)
- **subkey generation**
  - greater complexity makes cryptanalysis harder, but slows cipher
- **round function**
  - greater complexity can make analysis harder, but slows cipher
- **fast software en/decryption & ease of analysis**
  - are more recent concerns for practical use and testing

Feistel Cipher Decryption



Feistel Cipher Decryption

- Use the same encryption algorithm with:
- The ciphertext as the input,
- The round keys are applied in reverse order:

  Use Kn in the first round, and K1 in the 16th round.

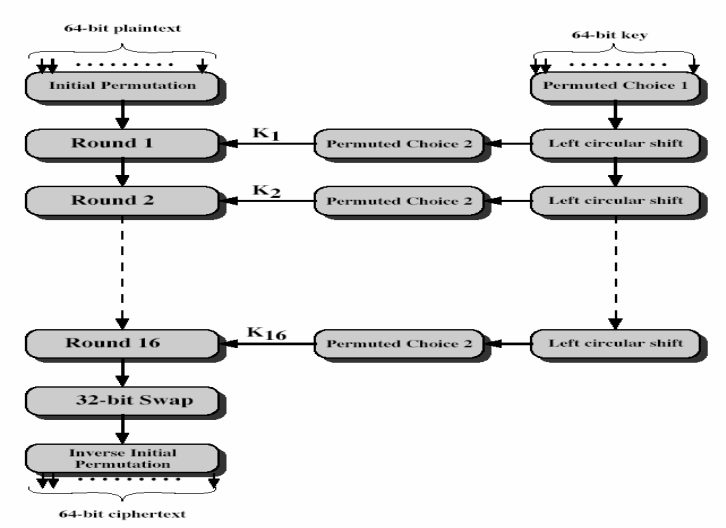
Data Encryption Standard (DES)

- most widely used block cipher in the world
- adopted in 1977 by NBS (now NIST) as FIPS PUB 46
- encrypts 64-bit data using 56-bit key
- IBM developed Lucifer cipher
  - by team led by Feistel
  - used 64-bit data blocks with 128-bit key
- in 1973 NBS issued request for proposals for a national cipher standard
- IBM submitted their revised Lucifer which was eventually accepted as the DES

DES Design Controversy

- although DES standard is public
- was considerable controversy over design
  - in choice of 56-bit key (vs Lucifer 128-bit)
  - and because design criteria were classified
- subsequent events and public analysis show in fact design was appropriate
- DES has become widely used, especially in financial applications

DES Encryption



Initial Permutation IP

- first step of the data computation
- IP reorders the input data bits
- even bits to LH half, odd bits to RH half
- quite regular in structure (easy in h/w)
- see text Table 3.2
- example:

```
IP(675a6967 5e5a6b5a) = (ffb2194d 004df6fb)
```

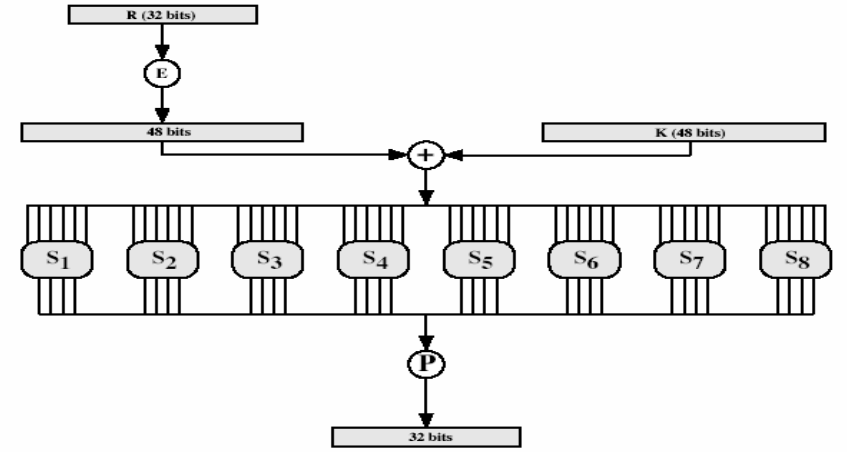

DES Round Structure

- uses two 32-bit L & R halves
- as for any Feistel cipher can describe as:

  $L_i = R_{i-1}$

  $R_i = L_{i-1}$ xor F(R_{i-1}, K_i)
- takes 32-bit R half and 48-bit subkey and:
  - expands R to 48-bits using perm E
  - adds to subkey
  - passes through 8 S-boxes to get 32-bit result
  - finally permutes this using 32-bit perm P

DES Round Structure



Substitution Boxes S

- have eight S-boxes which map 6 to 4 bits
- each S-box is actually 4 little 4 bit boxes
  - outer bits 1 & 6 (**row** bits) select one rows
  - inner bits 2-5 (**col** bits) are substituted
  - result is 8 lots of 4 bits, or 32 bits
- row selection depends on both data & key
  - feature known as autoclaving (autokeying)
- example:

```
S(18 09 12 3d 11 17 38 39) = 5fd25e03
```

DES Key Schedule

- forms subkeys used in each round
- consists of:
  - initial permutation of the key (PC1) which selects 56-bits in two 28-bit halves
  - 16 stages consisting of:
    - selecting 24-bits from each half
    - permuting them by PC2 for use in function f,
    - rotating **each half** separately either 1 or 2 places depending on the **key rotation schedule** K

DES Decryption

- decrypt must unwind steps of data computation
- with Feistel design, do encryption steps again
- using subkeys in reverse order (SK16 … SK1)
- note that IP undoes final FP step of encryption
- 1st round with SK16 undoes 16th encrypt round
- ….
- 16th round with SK1 undoes 1st encrypt round
- then final FP undoes initial encryption IP
- thus recovering original data value

Avalanche Effect

- A small change in the plaintext or the key should result in significant change in the ciphertext. It is a desirable property of encryption algorithm.
- where a change of **one** input or key bit results in changing approx **half** output bits
- making attempts to “home-in” by guessing keys impossible
- DES exhibits strong avalanche effect

Strength of DES – Key Size, DES Nature

- 56-bit keys have $2^{56} = 7.2 \times 10^{16}$ values
- brute force search looks hard
- recent advances have shown is possible
  - in 1997 on Internet in a few months
  - in 1998 on dedicated h/w (EFF) in a few days
  - in 1999 above combined in 22hrs!
- now considering alternatives to DES
- DES Algorithm Nature: The main concern was about the S-Boxes. No body discovered the weakness in them

Strength of DES – Timing Attacks

- Attacks the actual implementation of the cipher
- Observes how long it takes to decrypt a ciphertext using a certain implementation.
- Uses the fact that calculations can take varying times depending on the value of the applied inputs.
- Noticing the Hamming weight (# of 1's).
- DES is resistant to the timing attacks

Differential Cryptanalysis

- one of the most significant recent (public) advances in cryptanalysis
- published in 1990
- powerful method to analyse block ciphers
- used to analyse most current block ciphers with varying degrees of success
- DES reasonably resistant to it

Differential Cryptanalysis

- Finding the key by a chosen plaintext attack.
- a statistical attack against Feistel ciphers
- design of S-P networks has output of function *f* influenced by both input & key
- hence cannot trace values back through cipher without knowing values of the key

Differential Cryptanalysis Compares Pairs of Encryptions

- with a known difference in the input
- searching for a known difference in output
- when same subkeys are used

$$\begin{aligned}\Delta m_{i+1} &= m_{i+1} \oplus m'_{i+1} \\ &= \left[m_{i-1} \oplus \mathrm{f}\left(m_i, K_i\right)\right] \oplus \left[m'_{i-1} \oplus \mathrm{f}\left(m'_i, K_i\right)\right] \\ &= \Delta m_{i-1} \oplus \left[\mathrm{f}\left(m_i, K_i\right) \oplus \mathrm{f}\left(m'_i, K_i\right)\right]\end{aligned}$$

Linear Cryptanalysis

- another recent development
- also a statistical method
- must be iterated over rounds, with decreasing probabilities
- developed by Matsui et al in early 90's
- based on finding linear approximations
- can attack DES with 2^{47} known plaintexts, still in practise infeasible

Block Cipher Design Principles

- basic principles still like Feistel in 1970's
- number of rounds
  - more is better, exhaustive search best attack
- function f:
  - provides "confusion", is nonlinear, avalanche
- key schedule
  - complex subkey creation, key avalanche

Modes of Operation

- block ciphers encrypt fixed size blocks
- eg. DES encrypts 64-bit blocks, with 56-bit key
- need way to use in practise, given usually have arbitrary amount of information to encrypt
- Four standard modes were defined for DES
- Extended to five later, and they can be used with other block ciphers: 3DES and AES.

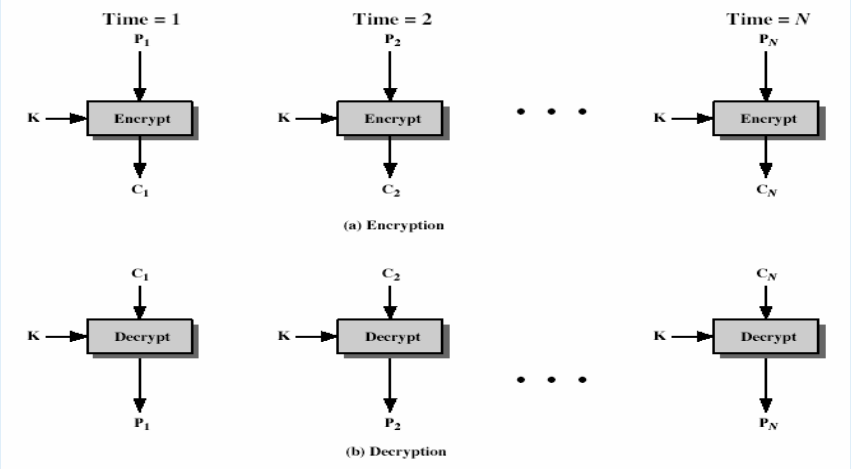
Electronic Codebook Book (ECB)

- message is broken into independent blocks which are encrypted
- each block is a value which is substituted, like a codebook, hence name
- each block is encrypted independently from the other blocks

  $C_i = DES_{K1}(P_i)$

- uses: secure transmission of single values

Electronic Codebook Book (ECB)



Advantages and Limitations of ECB

- repetitions in message may show in ciphertext
  - if aligned with message block
  - with messages that change very little, which become a code-book analysis problem
- weakness due to encrypted message blocks being independent
- main use is sending a few blocks of data

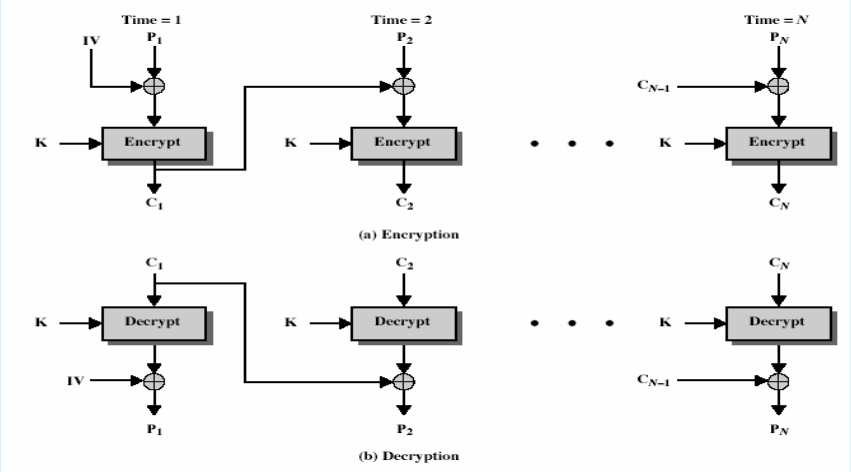
Cipher Block Chaining (CBC)

- message is broken into blocks
- but these are linked together in the encryption operation
- each previous cipher blocks is chained with current plaintext block, hence name
- use Initial Vector (IV) to start process

  $C_i = DES_{K1}(P_i \text{ XOR } C_{i-1})$

  $C_{-1} = IV$
- uses: bulk data encryption, authentication

Cipher Block Chaining (CBC)



Advantages and Limitations of CBC

- each ciphertext block depends on **all** message blocks
- thus a change in the message affects all ciphertext blocks after the change as well as the original block
- need **Initial Value** (IV) known to sender & receiver
  - however if IV is sent in the clear, an attacker can change bits of the first block, and change IV to compensate
  - hence either IV must be a fixed value or it must be sent encrypted in ECB mode before rest of message

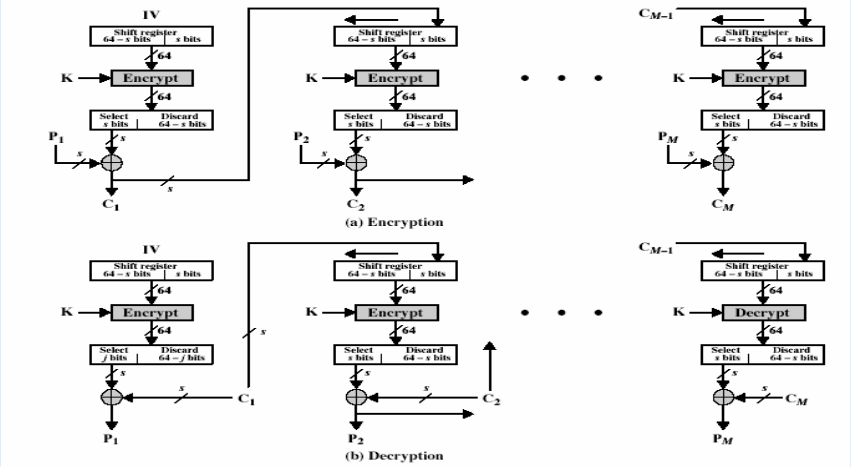
Cipher FeedBack (CFB)

- message is treated as a stream of bits
- added to the output of the block cipher
- result is feed back for next stage (hence name)
- standard allows any number of bit (1,8 or 64 or whatever) to be feed back
  - denoted CFB-1, CFB-8, CFB-64 etc
- is most efficient to use all 64 bits (CFB-64)

  $C_i = P_i \text{ XOR } DES_{K1}(C_{i-1})$

  $C_{-1} = IV$
- uses: stream data encryption, authentication

Cipher FeedBack (CFB)



Advantages and Limitations of CFB

- appropriate when data arrives in bits/bytes
- most common stream mode
- limitation is need to stall while do block encryption after every n-bits
- errors propagate for several blocks after the error

Output FeedBack (OFB)

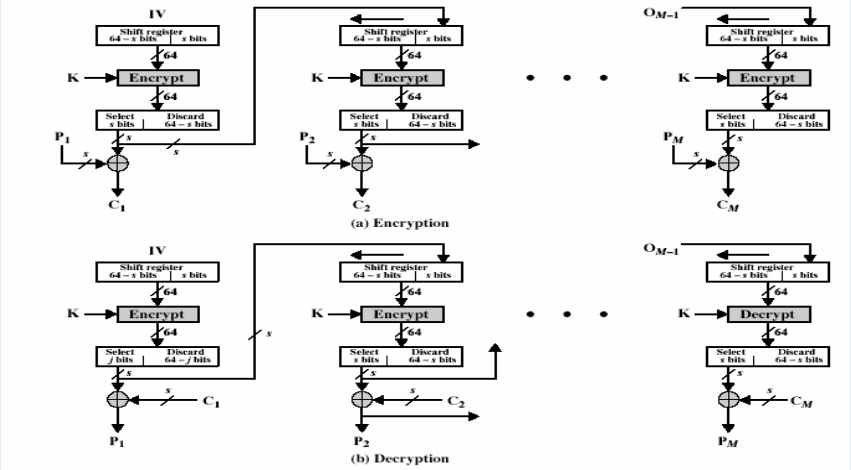
- message is treated as a stream of bits
- output of cipher is added to message
- output is then feed back (hence name)
- feedback is independent of message
- can be computed in advance

$C_i = P_i \text{ XOR } O_i$

$O_i = DES_{K1}(O_{i-1})$

$O_{-1} = IV$

Output FeedBack (OFB)



Advantages and Limitations of OFB

- used when error feedback a problem or where need to encryptions before message is available
- superficially similar to CFB
- but feedback is from the output of cipher and is independent of message
- sender and receiver must remain in sync, and some recovery method is needed to ensure this occurs
- originally specified with m-bit feedback in the standards
- subsequent research has shown that only **OFB-64** should ever be used

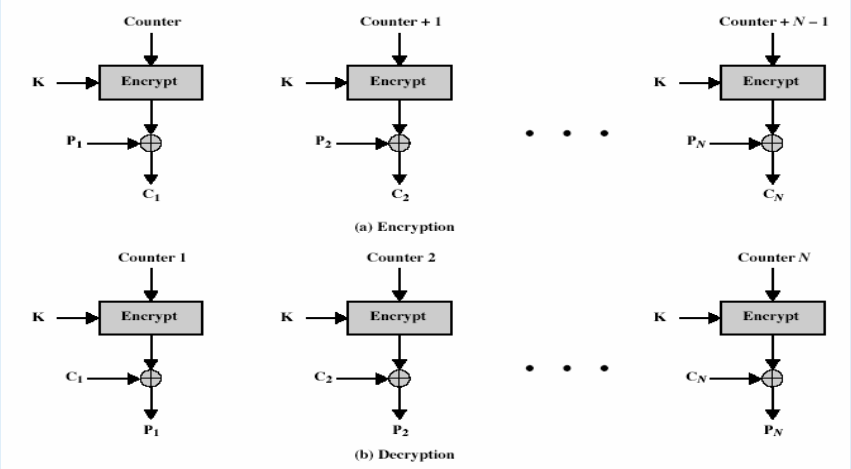
Counter (CTR)

- a "new" mode, though proposed early on
- similar to OFB but encrypts counter value rather than any feedback value
- must have a different counter value for every plaintext block (never reused)

  $C_i = P_i \text{ XOR } O_i$

  $O_i = DES_{K1}(i)$
- uses: high-speed network encryptions

Counter (CTR)



Advantages and Limitations of CTR

- efficiency
  - can do parallel encryptions
- random access to encrypted data blocks
- provable security (good as other modes)
- but must ensure never reuse key/counter values, otherwise could break (cf OFB)

Summary

- have considered:
  - block cipher design principles
  - DES
    - details
    - strength
  - Differential Cryptanalysis
  - Modes of Operation
    - ECB, CBC, CFB, OFB, CTR