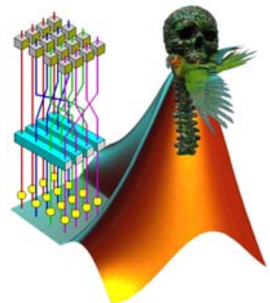


Crypto Basics

Cryptography Overview
Public vs. Private Key Cryptography
Classical / ancient ciphers
Modern ciphers: DES
Recent cipher: AES

1

What is a cryptosystem?

- $K = \{0,1\}^l$
- $P = \{0,1\}^m$
- $C' = \{0,1\}^n$, $C \subseteq C'$

- $E: P \times K \to C$
- $D: C \times K \to P$

- $\forall\ p \in P, k \in K: D(E(p,k),k) = p$
  - It is *infeasible* to find inversion $F: P \times C \to K$

Lets start again!
This time in English … .

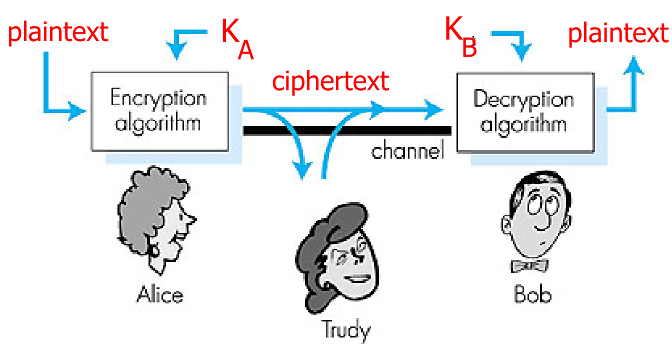
2

What is a cryptosystem?

- A pair of algorithms that take a key and convert plaintexts to ciphertexts and backwards later
  - Plaintext: text to be protected
  - Ciphertext: should appear like random
- Requires sophisticated math!
  - Do not try to design your own algorithms!

3

The language of cryptography



- Symmetric or secret key crypto:
  sender and receiver keys are identical and ***secret***
- Asymmetric or Public-key crypto:
  encrypt key public, decrypt key secret

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Attacks

- Opponent whose goal is to break a cryptosystem is the *adversary*
  - Assume adversary knows algorithm used, but not key

- Three types of attacks:
  - *ciphertext only*:
    - adversary has only ciphertext; goal is to find plaintext, possibly key
  - *known plaintext*:
    - adversary has ciphertext, corresponding plaintext; goal is to find key
  - *chosen plaintext*:
    - adversary may supply plaintexts and obtain corresponding ciphertext; goal is to find key

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Basis for Attacks

- Mathematical attacks
  - Based on analysis of underlying mathematics

- Statistical attacks
  - Make assumptions about the distribution of letters, pairs of letters (digrams), triplets of letters (trigrams), *etc.*
    - Called *models of the language*
  - Examine ciphertext, correlate properties with the assumptions.

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Example: Symmetric key cryptography

Substitution cipher: substituting one thing for another

- Monoalphabetic cipher: substitute one letter for another

```
plaintext:  abcdefghijklmnopqrstuvwxyz

ciphertext: mnbvcxzasdfghjklpoiuytrewq
```

E.g.: `Plaintext: bob. i love you. alice`
`ciphertext: nkn. s gktc wky. mgsbc`

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Monoalphabetic Cipher Security

- Total of 26! = 4 x 1026 keys
- So many keys, might think is secure
- **!!!WRONG!!!**
- Problem is language characteristics

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Language Redundancy and Cryptanalysis

- Human languages are **redundant**
- Eg "th lrd s m shphrd shll nt wnt"
- Letters are not equally commonly used
- In English E is by far the most common letter
  - followed by T,R,N,I,O,A,S
- Other letters like Z,J,K,Q,X are fairly rare
- Have tables of single, double & triple letter frequencies for various languages

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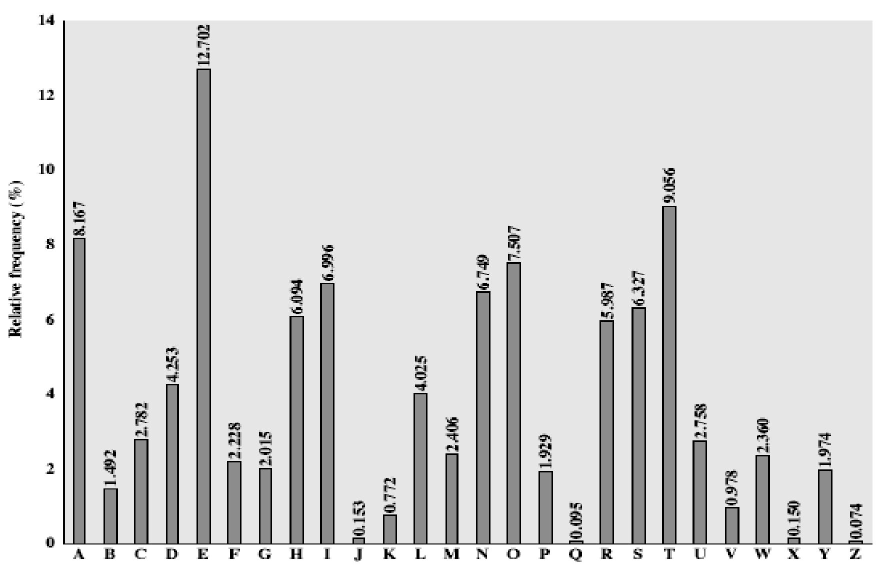
English Letter Frequencies



Use in Cryptanalysis

- Key concept
  - monoalphabetic substitution ciphers do not change relative letter frequencies
- Discovered by Arabian scientists in 9th century
- Calculate letter frequencies for ciphertext
- Compare counts/plots against known values
- For mono-alphabetic must identify each letter
  - tables of common double/triple letters help

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Properties of a good cryptosystem

- There should be no way short of enumerating all possible keys to find the key from any reasonable amount of ciphertext and/or plaintext, nor any way to produce plaintext from ciphertext without the key
- Enumerating all possible keys must be infeasible
- The ciphertext must be indistinguishable from true random values

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Milestones in modern cryptography

- 1883 Kerckhoffs' principles
- 1917-1918 Vernam/Mauborgne cipher (one-time pad)
- 1920s-1940s Mathematicization and mechanization of cryptography and cryptanalysis
- 1973 U.S. National Bureau of Standards issues a public call for a standard cipher; this led to the adoption of the Data encryption Standard (DES)

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Milestones in modern cryptography: Public key cryptography

- Merkle invents a public key distribution scheme
- 1976: Diffie and Hellman invent public key encryption and digital signatures, but do not devise a suitable algorithms with all desired properties
- 1977: Rivest, Shamir, and Adelman invent their algorithm RSA soon after
- 1973: Clifford Cocks, a British mathematician working for the UK intelligence agency GCHQ, described an equivalent system in an internal document in 1973.
  - His discovery, however, was not revealed until 1997 due to its top-secret classification, and Rivest, Shamir, and Adleman devised RSA independently of Cocks' work.

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Kerckhoffs' law

- „The system must not be required to be secret, and it must be able to fall into the hands of the enemy without inconvenience"

- In other words, the security of the system must rest entirely on the secrecy of the key not the algorithm itself

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Vernam/Mauborgne cipher

- Exclusive-OR a key stream tape with the plaintext

- Online encryption of teletype traffic, combined with transmission

- For a one-time pad – which is provably secure – use true-random keying tapes and never reuse the keying material

- Problem: how to get good long one-time pads
  - Reuse of keying material ⇒ stream cipher
  - Key stream via algorithm ⇒ no one-time pad

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Mathematicization and mechanization

- Mechanical encryptors
  (Vernam, Enigma, Hagelin, Scherbius)

- Mathematical cryptanalysis
  (Friedman, Rejewski et al., Bletchley Park)

- Machine-aided cryptanalysis
  (Friedman, Turing et al.)

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Hagelin Rotor Machine

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Standardized ciphers

- Until the 1970s, most strong ciphers were government secrets
- Spread of computers ⇒ new threads (Reportedly, soviets eavesdropped on U.S. grain negotiators' conversations)
- NBS (now called NIST) issued public call for cipher; eventually IBM responded

⇒ eventual result – via secret process - DES

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What we have today

- Encryption is completely computerized and operates on bits
- Basic primitives can be combined to produce powerful results
  - Difficult to verify combined result.
- Encryption is by far the strongest weapon of computer security
- Host and OS software is by far the weakest link
- Bad software breaks crypto – NEVER the cryptanalysis.

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Modern Block Ciphers

- Look at modern block ciphers
- One of the most widely used types of cryptographic algorithms
- Provides secrecy / authentication services
- Focus now on DES (Data Encryption Standard)
- Illustrate block cipher design principles

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Block vs. Stream Ciphers

- block ciphers process messages in blocks, each of which is then en/decrypted
- like a substitution on very big characters
  - 64-bits or more
- stream ciphers process messages a bit or byte at a time when en/decrypting
- many current ciphers are block ciphers
- broader range of applications

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Block Cipher Principles

- most symmetric block ciphers are based on a so called
  - **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

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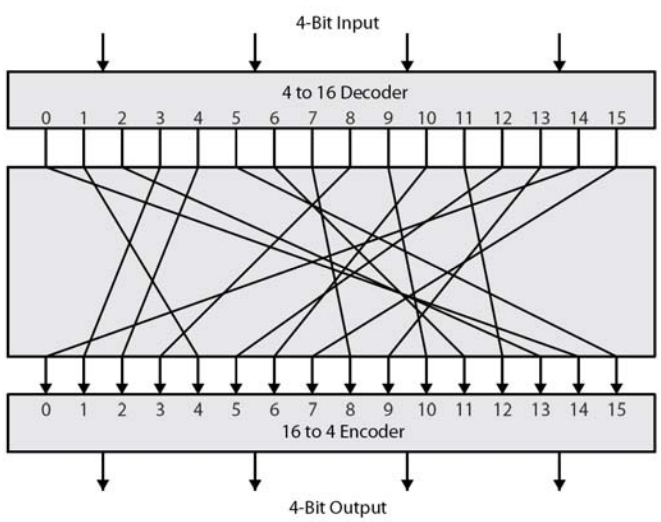
Ideal Block Cipher



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Claude Shannon and Substitution-Permutation Ciphers

- Claude Shannon introduced idea of substitution-permutation (S-P) networks in 1949 paper
- form basis of modern block ciphers
- S-P nets are based on the two primitive cryptographic operations seen before:
  - *substitution* (S-box)
  - *permutation* (P-box)
- provide *confusion* & *diffusion* of message & key

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Confusion and Diffusion

- cipher needs to completely obscure statistical properties of original message
- a one-time pad does this
- more practically Shannon suggested combining S & P elements to obtain:
  - **diffusion** – dissipates statistical structure of plaintext over bulk of ciphertext
  - **confusion** – makes relationship between ciphertext and key as complex as possible

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Feistel Cipher Structure

- Horst Feistel devised the **feistel 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 S-P net concept

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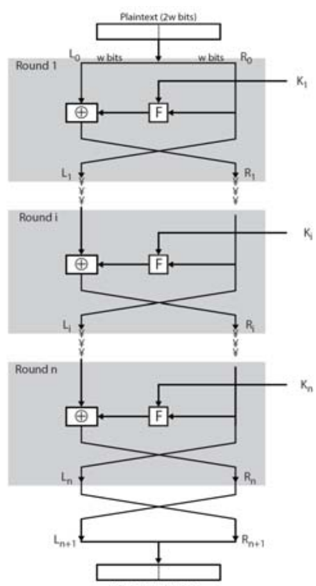
Feistel Cipher Structure



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Feistel Cipher Design Elements

- block size
- key size
- number of rounds
- subkey generation algorithm
- round function
- fast software en/decryption
- ease of analysis

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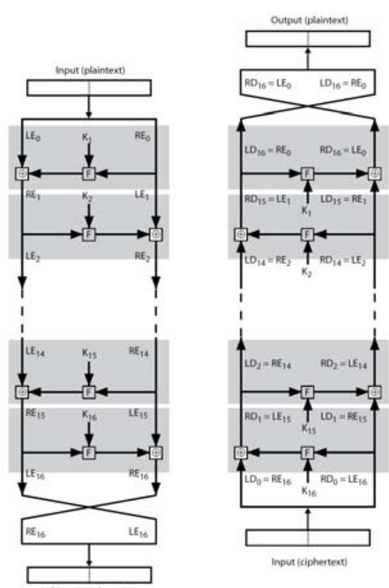
Feistel Cipher Decryption



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Data Encryption Standard (DES)

- most widely used block cipher in world
- adopted in 1977 by NBS (now NIST)
  - as FIPS PUB 46
- encrypts 64-bit data using 56-bit key
- has widespread use
- has been considerable controversy over its security

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DES History

- IBM developed Lucifer cipher
  - by team led by Feistel in late 60's
  - used 64-bit data blocks with 128-bit key
- then redeveloped as a commercial cipher with input from NSA and others
- in 1973 NBS issued request for proposals for a national cipher standard
- IBM submitted their revised Lucifer which was eventually accepted as the DES

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DESIGN 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
- use of DES has flourished
  - especially in financial applications
  - still standardised for legacy application use

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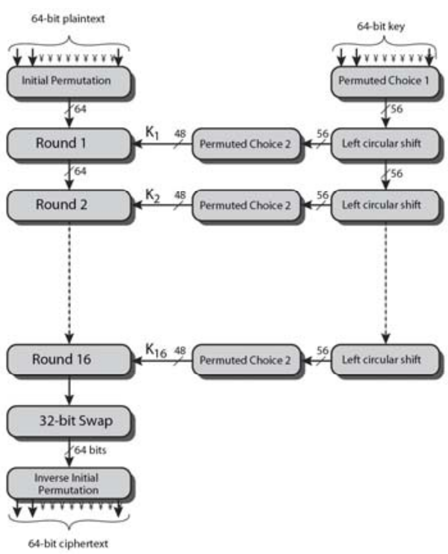
DES Encryption Overview



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

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DES Round Structure

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

  $L_i = R_{i-1}$

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

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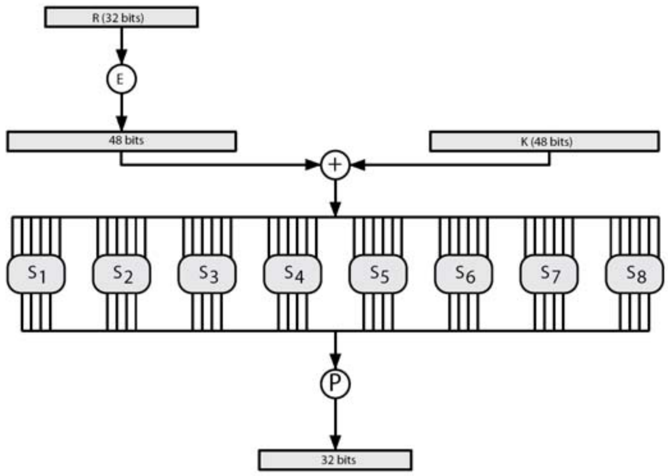
DES Round Structure



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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 row of 4
  - 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`**

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DES Key Schedule

- forms subkeys used in each round
  - initial permutation of the key (PC1) which selects 56-bits in two 28-bit halves
  - 16 stages consisting of:
    - rotating **each half** separately either 1 or 2 places depending on the **key rotation schedule** K
    - selecting 24-bits from each half & permuting them by PC2 for use in round function F
- note practical use issues in h/w vs. s/w

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DES Decryption

- decrypt must unwind steps of data computation
- with Feistel design, do encryption steps again using subkeys in reverse order (SK16 … SK1)
  - 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

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Avalanche Effect

- key desirable property of encryption alg
- 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

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Strength of DES – Key Size

- 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!
- still must be able to recognize plaintext
- must now consider alternatives to DES – later more on AES

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Strength of DES – Analytic Attacks

- now have several analytic attacks on DES
- these utilise some deep structure of the cipher
  - by gathering information about encryptions
  - can eventually recover some/all of the sub-key bits
  - if necessary then exhaustively search for the rest
- generally these are statistical attacks
- include
  - differential cryptanalysis
  - linear cryptanalysis
  - related key attacks

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Differential Cryptanalysis

- one of the most significant recent (public) advances in cryptanalysis
- known by NSA in 70's cf DES design
- Murphy, Biham & Shamir published in 90's
- powerful method to analyse block ciphers
- used to analyse most current block ciphers with varying degrees of success
- DES reasonably resistant to it, cf. Lucifer

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Differential Cryptanalysis

- a statistical attack against Feistel ciphers
- uses cipher structure not previously used
- design of S-P networks has output of function *f* influenced by both input & key
- hence cannot trace values back through cipher without knowing value of the key
- differential cryptanalysis compares two related pairs of encryptions

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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

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

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Differential Cryptanalysis

- have some input difference giving some output difference with probability p
- if find instances of some higher probability input / output difference pairs occurring
- can infer subkey that was used in round
- then must iterate process over many rounds (with decreasing probabilities)

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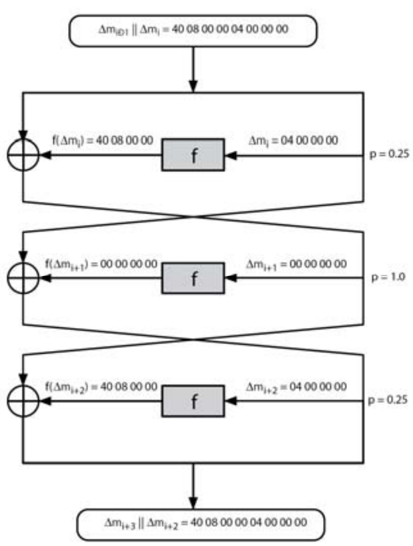
Differential Cryptanalysis



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Differential Cryptanalysis

- perform attack by repeatedly encrypting plaintext pairs with known input XOR until obtain desired output XOR
- when found
  - if intermediate rounds match required XOR have a **right pair**
  - if not then have a **wrong pair**
- can then deduce keys values for the rounds
  - right pairs suggest same key bits
  - wrong pairs give random values
- for large numbers of rounds, probability is so low that more pairs are required than exist with 64-bit inputs
- Biham and Shamir have shown how a 13-round iterated characteristic can break the full 16-round DES

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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^{43} known plaintexts, easier but still in practise infeasible

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Linear Cryptanalysis

- find linear approximations with prob p != ½
  $P[i_1,i_2,...,i_a] \oplus C[j_1,j_2,...,j_b] = K[k_1,k_2,...,k_c]$
  where i_a,j_b,k_c are bit locations in P,C,K
- gives linear equation for key bits
- get one key bit using max likelihood alg
- using a large number of trial encryptions
- effectiveness given by: $|p-{}^1/_2|$

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DES Design Criteria

- as reported by Coppersmith in [COPP94]
- 7 criteria for S-boxes provide for
  - non-linearity
  - resistance to differential cryptanalysis
  - good confusion
- 3 criteria for permutation P provide for
  - increased diffusion

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Block Cipher Design

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

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How to use a block cipher

- Direct use of a block cipher is inadvisable
  - Enemy can build up „code book" of plaintext/ciphertext equivalents
  - Only works for messages that are a multiple of the block size
- Solution: 5 standard modes of operation
  - Electronic Code Book (ECB)
  - Cipher Block Chaining (CBC)
  - Cipher Feedback (CFB)
  - Output Feedback (OFB)
  - Counter (CTR)

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Codes vs. Ciphers

- Ciphers operate syntactically, on elements of an alphabet (letters) or groups of “letters”:
  A $\rightarrow$ D, B $\rightarrow$ C, etc.

- Codes operate semantically, on words, phrases, or sentences, e.g., per codebooks

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Electronic Code Book

- Direct use of block cipher

- Used primarily to transmit encrypted keys

- Very weak for general-purpose encryption

- Problem: block substitution attack

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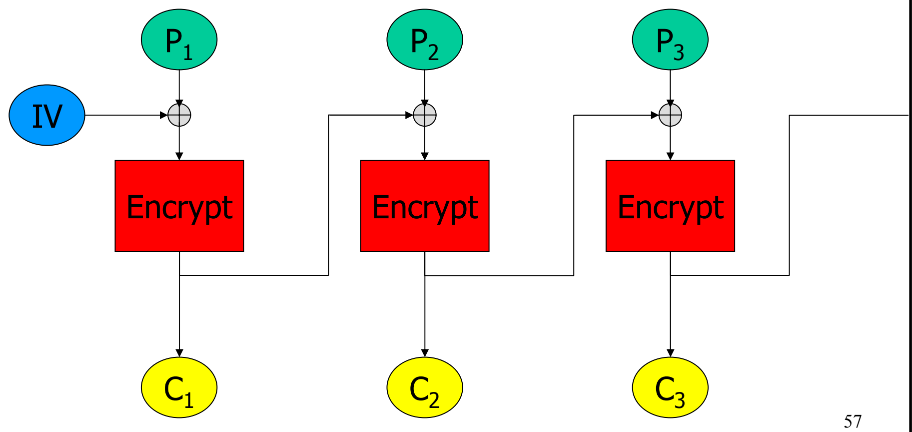
Cipher Block Chaining (CBC)

- IV: Initialization vector, P: plaintext, C: ciphertext



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Cipher Block Chaining

- Properties of CBC
  - Ciphertext of each encrypted block depends on the plaintext of all preceding blocks
  - Subsets of blocks appear valid and will decrypt properly
  - Message integrity has to be done otherwise
- CBC and electronic voting
  [Kohno, Stubblefield, Rubin, Wallach]
  - Found in the source code for Diebold voting machines:
  - `DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data, totalSize, DESKEY, NULL, DES_ENCRYPT)`

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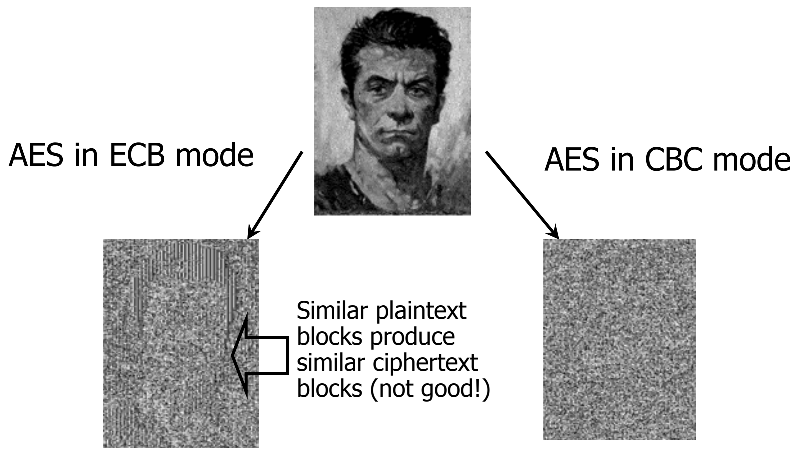
ECB vs. CBC

[Picture due to Bart Preneel]



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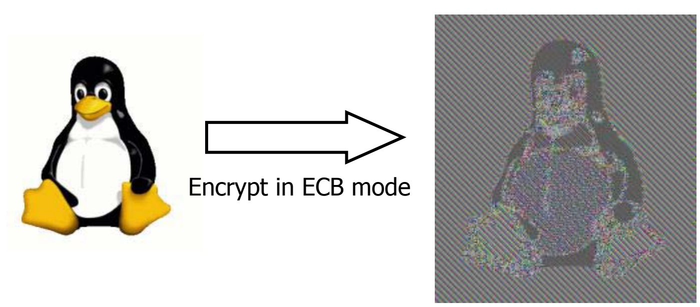
Information leakage in ECB mode

[Wikipedia]



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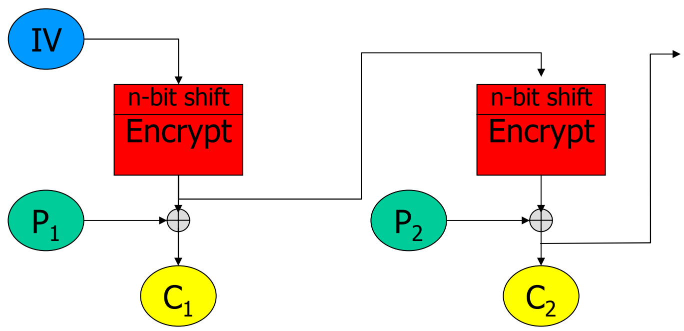
n-Bit Cipher Feedback

- Add n-bit shift and move Encrypt operation before X-OR operator
- Retains some of the previous cycle's ciphertext
- Copes gracefully with deletion of n-bit unit (bit errors)



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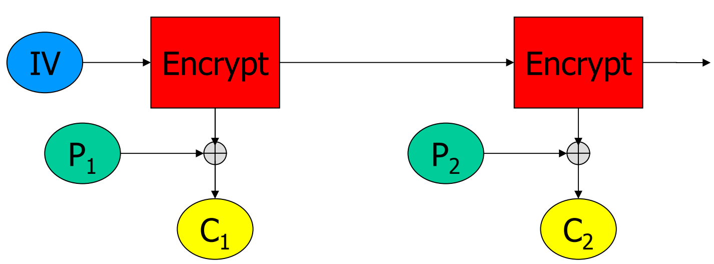
n-Bit Output Feedback

- No error propagation
- Active attacker can make controlled changes to plaintext
- OFB is a form of stream cipher



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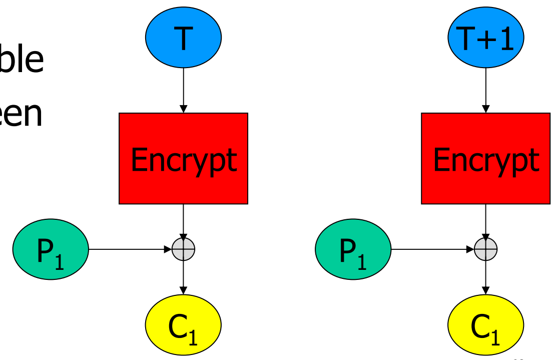
Counter mode

- Another form of stream cipher
- Counter often split in message and block number
- Active attack can make controlled changes to plaintext
- Highly parallelizable
- No linkage between stages
- Vital: Counter never to repeat



Which mode for what task

- General file or packet encryption: CBC
  $\Rightarrow$ Input must be padded to n $\times$ cipher block size
- Risk of byte or bit deletion: CFB_8 or CFB_1
- Bit stream: noisy line and error propagation is undesirable: OFB
- Very high-speed data: CTR
- Needed in most situations: integrity checks
  - Actually needed almost always
  - Attack on integrity $\Rightarrow$ attack on confidentiality
  - Solution: separate integrity check along with encryption

Stream ciphers

- Operation:
  - Key stream generator produces a sequence S of pseudo-random bytes
  - Key stream bytes are combined (usually via XOR) with plaintext bytes

- Properties:
  - Very good for asynchronous traffic
  - Best-known stream cipher RC4 (used, e.g., in SSL)
  - Key stream must never be reused for different plaintexts

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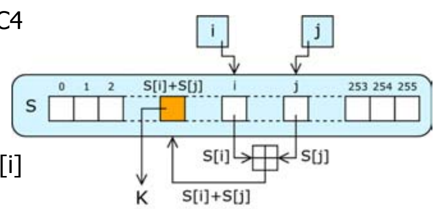
RC4

- Extremely efficient
- After key setup, it just produces a key stream
- Internal state: 256-byte array plus two integers

For as many iterations as are needed, the RC4 modifies the state and outputs a byte of the keystream. In each iteration, it increments *i*, adds the value of S pointed to by *i* to *j*, exchanges the values of S[*i*] and S[*j*], and then outputs the value of S at the location S[i] + S[j] (modulo 256). Each value of S is swapped at least once every 256 iterations.



- No resynchronization except via rekeying + starting over
- Note:
  known weaknesses if used other than as stream cipher

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CPU speed vs. key size

- Adding one bit to the key doubles work for brute force attack
- Effect on encryption time is often negligible or even free
- It costs nothing to use a longer RC4 key
- Going from 128-bit AES to 256-bit AES takes (at most) 40% longer for en-/decryption but increases the attacker's effort by a factor of 2^{128}
- Using triple DES costs $3\times$ more to encrypt, but increases the attacker's effort by a factor of 2^{112}
- Moore's Law favors the defender!

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Summary

- Have considered:
  - Block vs stream ciphers
  - Feistel cipher design & structure
  - DES
    - details
    - strength
  - Differential & Linear Cryptanalysis
  - Block cipher design principles

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