Cryptography and its Applications Part I

egassem siht daer uoy naC?

Ubj nobhg guvf bar?

Additional Reference

Alfred J. Menezes, Paul C. van Oorschot, and Scott A. Vanstone. **Handbook of Applied Cryptography**, CRC Press, Boca Raton, FL, 1999. (All chapters available for free download at http://www.cacr.math.uwaterloo.ca/hac)

Cryptography

- Cryptography means hidden writing
- Comes from the Greek words
  - κρυπτω (hidden or secret) and
  - γραφω (writing)
- A tool for
  - secrecy
  - integrity
  - authentication
  - non-repudiation

  to counter passive and active attacks

Terminology

- **Encryption** (encoding, enciphering)— The process of coding a message so that its meaning is concealed
- **Decryption** (decoding, deciphering)— The process of transforming an encrypted message into the original form
- **Cryptosystem** — A system for encryption and decryption
- **Plaintext** or **cleartext** — A message in its original form
- **Ciphertext** — A message in the encrypted form

Different types of Algorithms

- **Restricted** Algorithm
  - *The security of a restricted algorithm requires keeping the algorithm secret.*
- **Key-Based** Algorithm
  - *The security of key-based algorithms is based on the secrecy of the algorithm, the secrecy of the key(s), or both.*
- Secret/**Symmetric Key** System
  - *Single Key for both encryption and decryption*
- Public/ **Asymmetric Key** System
  - *Two Keys: one to encrypt and one to decrypt*

Stream and Block Ciphers

- Stream ciphers convert each symbol of plaintext into a symbol of ciphertext
- For block ciphers, break the plaintext into strings (called blocks) of fixed length and encrypt one block at a time
- Most well-known symmetric key encryption schemes are fixed-size block ciphers
- Most common block sizes
  - 64 (DES, 3DES, …)
  - 128 (RC5, AES, …)
  - Variable (in RSA it depends on the value of n)

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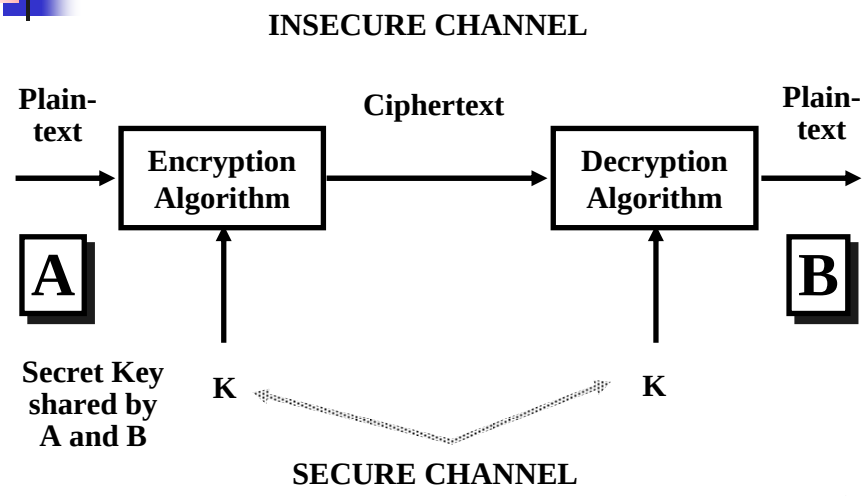
Secret Key Cryptosystem



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Notation

- C = E(K,M)
- M = D(K,C)

- K: Key
- E: Encryption Algorithm
- D: Decryption Algorithm
- M: Plaintext Message
- C: Ciphertext Message

- Confidentiality depends only on the secrecy of the key
- Secret key systems do not scale well:
  - With N parties, necessary to generate and distribute N*(N-1)/2 keys
- Long-term vs. Session keys
  - Prolonged use increases the exposure
  - Short-term keys communicated using the long-term key

Cryptanalysis

- Cryptanalyst is assumed to know E and D
- Objective of cryptanalyst is to discover the secret key K

(real objective: discover the plaintext message M, but this is generally assumed to be equivalent to discovering K)

- **Ciphertext Only:** Cryptanalyst only knows ciphertext
- **Known Plaintext:** Cryptanalyst knows some plaintext-ciphertext pairs
- **Chosen Plaintext:** Cryptanalyst knows some plaintext-ciphertext pairs for plaintext of the cryptanalyst's choice
- **Chosen Ciphertext:** Cryptanalyst knows some plaintext-ciphertext pairs for ciphertext of the cryptanalyst's choice

Known Plaintext Attack

- 40 bit key requires 2^{39} (approx. $5*10^{11}$) trials on average (could be exported from USA even before 2000)
- 56 bit key (DES) requires 2^{55} (approx. $3.6*10^{16}$) trials
- 80 bit key (Clipper chip) requires 2^{79} (approx. $6*10^{23}$) trials
- 128 bit key (IDEA) requires 2^{127} (approx. $2*10^{38}$) trials

Trials/second	40 bit	56 bit	80 bit	128 bit
		time required		
1	20,000 years	10^9 yrs	10^{16} yrs	10^{30}
10^3	20 years	10^6 yrs	10^{13} yrs	10^{27} yrs
10^6	6 days	10^3 yrs	10^{10} yrs	10^{24} yrs
10^9	9 minutes	1 year	10^7 yrs	10^{21} yrs
10^{12}	0.5 seconds	10 hours	10^4 yrs	10^{18} yrs

Basic Encryption Techniques

- **Substitution**
- Permutation (or transposition)
- Combinations and iterations of these

Caesar Cipher 1

- earliest known substitution cipher
- by Julius Caesar
- first attested use in military affairs
- replaces each letter by 3rd letter on
- example:
  - `meet me after the toga party`
  - `PHHW PH DIWHU WKH WRJD SDUWB`

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Caesar Cipher 2

- can define transformation as:

```
a b c d e f g h i j k l m n o p q r s t u v w x y z
D E F G H I J K L M N O P Q R S T U V W X Y Z A B C
```

- assign to each letter a number

```
a b c d e f g h i j k  l  m
0 1 2 3 4 5 6 7 8 9 10 11 12
n  o  p  q  r  s  t  u  v  w  x  y  z
13 14 15 16 17 18 19 20 21 22 23 24 25
```

- then have Caesar cipher as:

  $C = E(p) = (p + k) \bmod 26$

  $p = D(C) = (C - k) \bmod 26$

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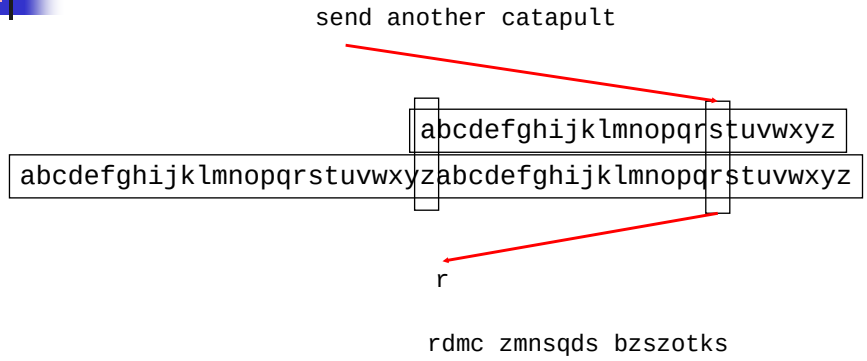
Substitutions: Caesar



Monoalphabetic cipher

- Easy to memorize
- Safe - few could read
- Patterns easy to see

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Cryptanalysis of Caesar Cipher

- only have 26 (actually 25) possible ciphers
  - A maps to A,B,..Z
- could simply try each in turn
- a **brute force search**
- given ciphertext, just try all shifts of letters
- do need to recognize when have plaintext
  (easy for humans, not so for machines)
- eg. break ciphertext "GCUA VQ DTGCM"

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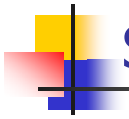


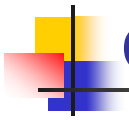
Simple Alphabetic Substitution

Example key

Plaintext ABCDEFGHIJKLMNOPQRSTUVWXYZ

Ciphertext PZQSGIMBWXDFKJVCHAOLUTERYN

- Huge key space: 26! ≈ 10**24
  - (~ number of atoms in a gallon of water)
- Trivially broken by known plaintext attack
- Easily broken with ciphertext only attack (for natural language plaintext)



Cryptosystem

- Quintuple ($\mathcal{E}$, $\mathcal{D}$, $\mathcal{M}$, $\mathcal{K}$, C)
  - $\mathcal{M}$ set of plaintexts
  - $\mathcal{K}$ set of keys
  - C set of ciphertexts
  - $\mathcal{E}$ set $\{ E_k : \mathcal{M} \rightarrow C \mid k \in \mathcal{K} \}$ of encryption functions
  - $\mathcal{D}$ set $\{ D_k : C \rightarrow \mathcal{M} \mid k \in \mathcal{K} \}$ of decryption functions

Example

- Example: Cæsar cipher
  - $\mathcal{M}$ = { sequences of letters }
  - $\mathcal{K}$ = { i | i is an integer and $0 \le i \le 25$ }
  - $\mathcal{E}$ = { E_k | for all $k \in \mathcal{K}$ and for all letters m, $E_k(m) = (m + k) \bmod 26$ }
  - $\mathcal{D}$ = { D_k | for all $k \in \mathcal{K}$ and for all letters c, $D_k(c) = (26 + c - k) \bmod 26$ }
  - $C = \mathcal{M}$

Monoalphabetic Cipher

"XBW HGQW XS ACFPSUWG FWPGWXF
CF AWWKZV CDQGJCDWA CD BHYJD
DJXHGW; WUWD XBW ZWJFX
PHGCSHF YCDA CF GSHFWA LV XBW
KGSYCFW SI FBJGCDQ RDSOZWAQW
OCXBBWZA IGSY SXBWGF."

Can we analyze it?

Frequency Analysis

"XBW HGQW XS ACFPSUWG FWPGWXF CF
AWWKZV CDQGJCDWA CD BHYJD DJXHGW;
WUWD XBW ZWJFX PHGCSHF YCDA CF
GSHFWA LV XBW KGSYCFW SI FBJGCDQ
RDSOZWAQW OCXBBWZA IGSY SXBWGF."

W: 20 C: 11 F: 11 G: 11

"Normal" English:

e 12% t 9% a 8%

Pattern Analysis

"XBe HGQe XS ACFPSUeG FePGeXF CF
AeeKZV CDQGJCDeA CD BHYJD DJXHGe;
eUeD XBe ZeJFX PHGCSHF YCDA CF
GSHFeA LV XBe KGSYCFe SI FBJGCDQ
RDSOZeAQe OCXBBeZA IGSY SXBeGF."

XBe = "the"

Most common tri-grams in English:

the = 6.4%

and = 3.4%

Guessing

"the HGQe tS ACFPSUeG FePGetF CF AeeKZV CDQGJCDeA CD hHYJD DJtHGe; eUeD the ZeJFt PHGCSHF YCDA CF GSHFeA LV the KGSYCFe SI FhJGCDQ RDSOZeAQe OCthheZA IGSY StheGF."

S = "o"

(what else could "tS" be ?)

Guessing

"the HGQe to ACFPoUeG FePGetF CF AeeKZV CDQGJCDeA CD hHYJD DJtHGe; eUeD the ZeJFt PHGCoHF YCDA CF GoHFeA LV the KGoYCFe oI FhJGCDQ RDoOZeAQe OCthheZA IGoY otheGF."

otheGF = "others"

Guessing

"the HrQe to ACsPoUer sePrets Cs AeeKZV CDQrJCDeA CD hHYJD DJtHre; eUeD the ZeJst PHrCoHs YCDA Cs roHseA LV the KroYCse oI shJrCDQ RDoOZeAQe OCthheZA IroY others."

"sePrets" = "secrets"

Guessing

"the HrQe to ACscoUer secrets Cs AeeKZV CDQrJCDeA CD hHYJD DJtHre; eUeD the ZeJst cHrCoHs YCDA Cs roHseA LV the KroYCse oI shJrCDQ RDoOZeAQe OCthheZA IroY others."

"ACscoUer" = "discover"

Guessing

"the HrQe to discover secrets is
deeKZV iDQrJiDed iD hHYJD DJtHre;
eveD the ZeJst cHrioHs YiDd is
roHsed LV the KroYise oI shJriDQ
RDoOZedQe OithheZd IroY others."

More guessing: H=u, Q=g, Y=m, I=f, D=n, O=w

Finally !

"the urge to discover secrets is
deeply ingrained in human nature;
even the least curious mind is
roused by the promise of sharing
knowledge withheld from others."

Why was it so easy?

- Does not hide statistical properties of the plaintext
- Does not hide the relationships in the plaintext (EE cannot match dg)
- English (and all natural languages) are very redundant: about 1.3 bits of information per letter
  - Compress English with gzip – about 1:6

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How to make it harder?

- Cosmetic
- Hide statistical properties:
  - Encrypt "e" with 12 different symbols, "t" with 9 different symbols, etc.
  - Add nulls, remove spaces
- Polyalphabetic cipher
  - Use different substitutions
- Transposition/Permutation
  - Scramble order of letters

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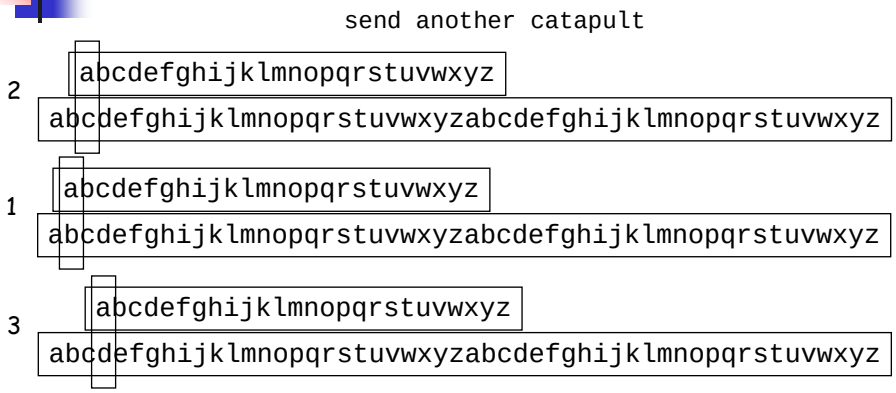
Substitutions: 213



Polyalphabetic Substitution Cipher

Ufqf bqqukgs fcudrvov

- Reduces patterns
- smooth out distribution

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Vigenere Tableau

- A Polyalphabetic Substitution Cipher
- Invented by Blaise de Vigenère, ~1550
- Considered unbreakable for 300 years
- Broken by Charles Babbage but kept secret to help British in Crimean War. Attack discovered independently by Friedrich Kasiski, 1863.
- Uses a keyword combined with message text and 26 possible alphabet permutations to smooth distribution

M = SEND ANOTHER CATAPULT
K = h a i l c e a s e r h a i l c e a s e
C = z e v o c r o l l v y c i e c t u d x

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Vigenère Simplification

- Use binary alphabet:

$$C_i = (P_i + K_{i \bmod N}) \bmod 2$$

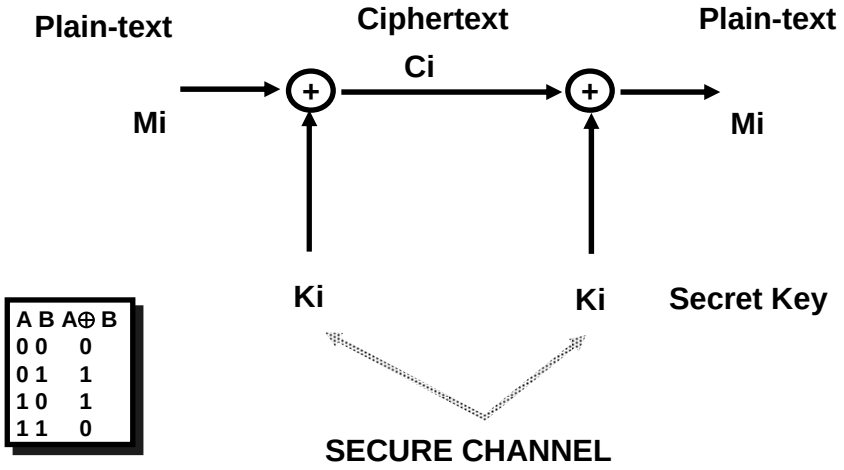
$$C_i = P_i \oplus K_{i \bmod N}$$

- Use a key as long as P:

$$C_i = P_i \oplus K_i$$

- One-time pad – perfect cipher!

Perfect Secrecy: Vernam One-time Pad



A	B	A⊕B
0	0	0
0	1	1
1	0	1
1	1	0

Perfect Secrecy

- The Vernam one-time pad is the ultimate cipher but is impractical for most situations
- Requires a random key longer than the message
- **Theorem:** If a cipher is perfect, there must be at least as many keys (l) as there are possible messages (n).
- The key cannot be reused
- Known plaintext reveals the portion of the key that has been used, but does not reveal anything about the future bits of the key

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Basic Encryption Techniques

- Substitution
- **Permutation** (or transposition)
- Combinations and iterations of these

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Simple Permutation

Plaintext	1	2	3	4
Ciphertext	4	3	1	2

A permutation is a reordering of the elements

- G E O R G E b M A S O N
- Divide into blocks, say of size 4 (the size of the key)
  G E O R G E b M A S O N
- Apply the key to each block
  R O G E M b G E N O A S

Simple Permutation

- Key space is (N!) when blocks have size N
- Trivially broken using known-plaintext attack
- Easily broken using ciphertext-only attack (for natural language plaintext)
- Multiple encipherment does not help (there is no point in doing two permutations in sequence)

Product Ciphers

- Substitution followed by permutation followed by substitution followed by permutation
- Best known example is DES (Data Encryption Standard)
- Mathematics to design a strong product cipher is classified
- For known plaintext/chosen-plaintext/chosen-ciphertext breakable by exhaustive search of key space.
- Therefore security is based on computational complexity of computing the key under these scenarios

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Data Encryption Standard (DES)

- DES is a product cipher with 56 bit key and 64 bit block size for plaintext and ciphertext
- Developed by IBM and in 1977 adopted by NIST (FIPS publication 46), with NSA approval, for unclassified information
- Adopted as ANSI DEA (Data Encryption Algorithm)
- Still used by the public sector
- E and D are public, but the design principles are classified
- Has some weak keys which are identified as part of the standard and should not be used

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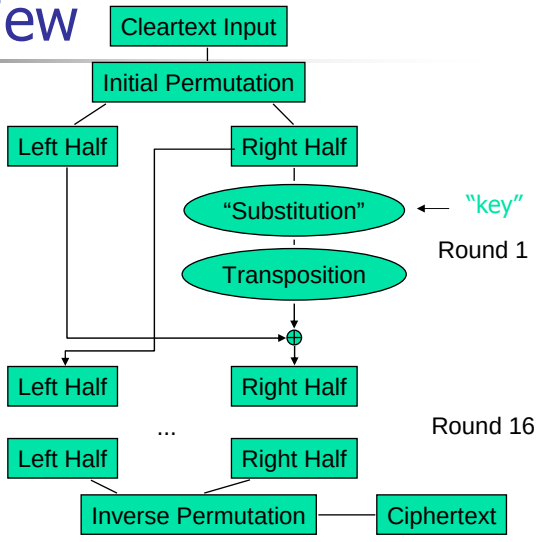
DES

- 1977 Approved as a Federal standard with 5 year cycle of re-certification
- 1987 Reluctantly re-approved for 5 years
- 1993 Approved for another 5 years
- 1999 NIST could no longer support the use of DES
  - Phase out use of Single DES (permitted in legacy systems only)
  - Use Triple DES
- October 2, 2000 A new encryption standard was announced, but Triple DES remains an approved algorithm (for US Government use) for the foreseeable future

DES Overview

- 16 rounds of permutation and transposition
- Swap halves after each round
- XOR left half with right half



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
    - S-boxes may have backdoors
- subsequent events and public analysis show in fact design was appropriate
  - Differential cryptanalysis less effective
- DES became widely used, especially in financial applications

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Undesirable Properties

- 4 weak keys
  - They are their own inverses
- 12 semi-weak keys
  - Each has another semi-weak key as inverse
- Complementation property
  - $DES_k(m) = c \Rightarrow DES_{k'}(m') = c'$
- S-boxes exhibit irregular properties
  - Distribution of odd, even numbers non-random
  - Outputs of fourth box depends on input to third box

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DES security

- Stood up remarkably well against nearly 20 years of public cryptanalysis (brute-force)
- brute-force attack now *quite* feasible: in 1998 a specially designed DES "cracking machine" costing $250,000 successfully cracked an encrypted message taking only 56 hours (and exhausting only ¼ of the keys in doing so)
- Another distributed Internet project took only 22 hours and 15 minutes
- What next ? (now that the 56 bit key is broken)
  - Double and triple DES
  - An entirely new cipher

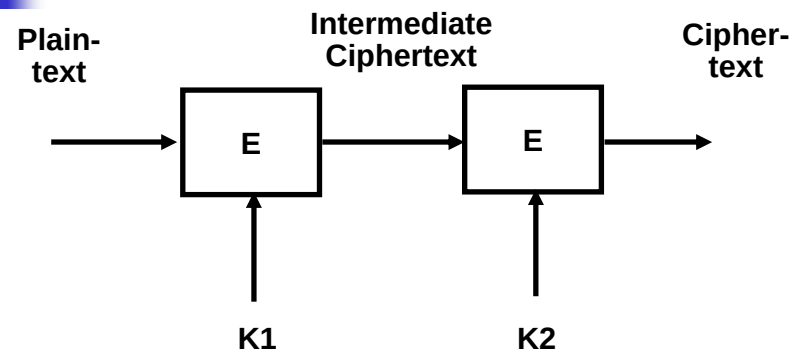
DES Multiple Encipherment

- In 1992 it was shown that DES is not a group: Two DES encryptions by DES are not equivalent to a single encryption

E(K2, E(K1,M)) is not equal to E(K3, M) for any K3

- So multiple encipherment should be effective

Double DES



- In a known-plaintext meet-in-the-middle attack (discovered by Diffie+Hellman) this amounts to an effective 57 bit key rather than the 112 bits one would expect

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Meet in the middle attack

- In a two-adjacent block ciphers such as double DES

  Cypher = E_{K2} (E_{K1} (Plain))

but

Intermediate= E_{K1}(Plain) = D_{K2} (Cypher)

so given a known pair [Plain, Cypher]

  - encrypt Plain with 2^{56} keys
  - decrypt Cypher with 2^{56} keys
  - compare to find match; double check
  - if OK, then you have the two keys

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TDEA : triple DES

- Technique suggested by Tuchman (IBM) for use in financial applications
- Approved as ANSI standard X9.17 in 1985 and incorporated in DES standard in 1999 as FIPS 46-3:
  - Approved conventional encryption algorithm.
  - Suggested move of legacy systems from DEA to TDEA.
  - Should coexist with new Advanced Encryption Standard
- put multiple DES units in sequence, i.e.

  Cypher = $E_{K3}(E_{K2}(E_{K1}\ (\text{Plain})))$
- extends key size as there is no K4, Cypher = $E_{K4}(\text{Plain})$
  - why triple? to avoid "meet in the middle" attack.
- Advantage: No known practical attacks
- Disadvantage: It is 3 times slower.

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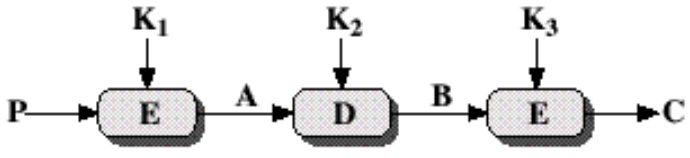
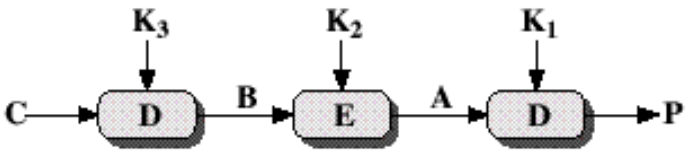
Encryption & Decryption



(a) Encryption



(b) Decryption

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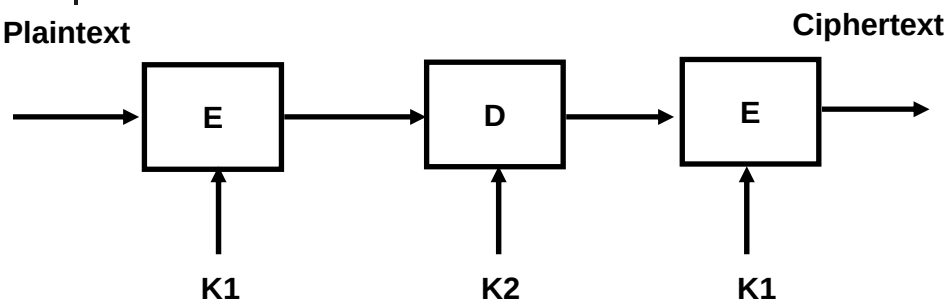
Triple DES



FIPS 46-3 allows for the use of two keys, $K_1 = K_3$, maintaining the effective key length of 112 bits (making a brute-force attack impractical)

Popular variation since "backward compatible":

if K2=K1, this reduces to a single DES encryption.

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Modes of Operation

- block ciphers encrypt fixed size blocks
  - eg. DES encrypts 64-bit blocks, with 56-bit key
- need way to use in practice, with arbitrary amount of information to encrypt
- four were defined for DES in ANSI standard **ANSI X3.106-1983 Modes of Use**
- now have 5 for DES and AES
- have **block** and **stream** modes

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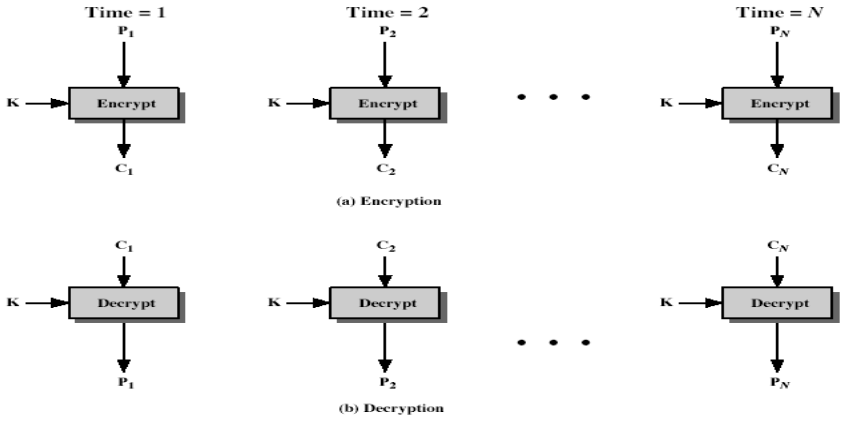
Electronic Codebook Book (ECB)

- 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 encoded independently of the other blocks

  $C_i = DES_{K1}(P_i)$
- uses: secure transmission of single values

Electronic Codebook Book (ECB)



Advantages/Limitations of ECB

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

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Cipher Block Chaining (CBC)

- message is broken into blocks that are linked together in the encryption operation
- each previous cipher blocks is chained with current plaintext block
- 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

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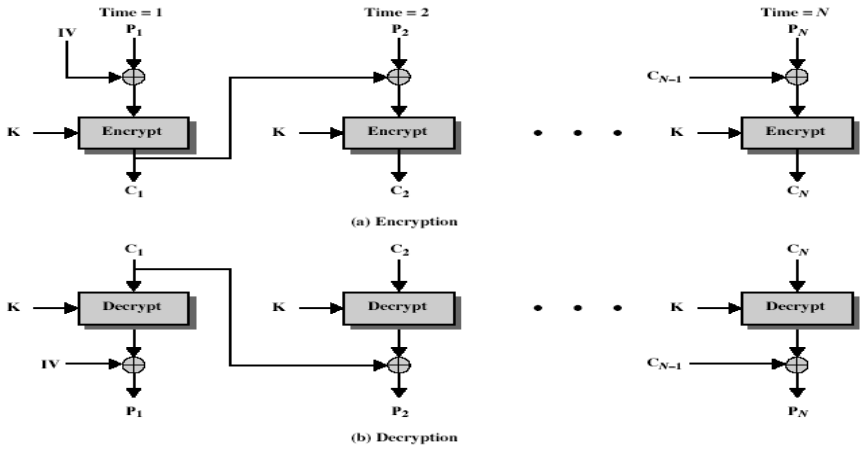
Cipher Block Chaining (CBC)



Advantages/Limitations of CBC

- each ciphertext block depends on **all** message blocks
- thus change in message affects all ciphertext blocks after change and original block
- need **Initial Value** (IV) known to sender and receiver
- at end of message, handle possible last short block by padding either with known non-data value (eg nulls) or pad last block with count of pad size

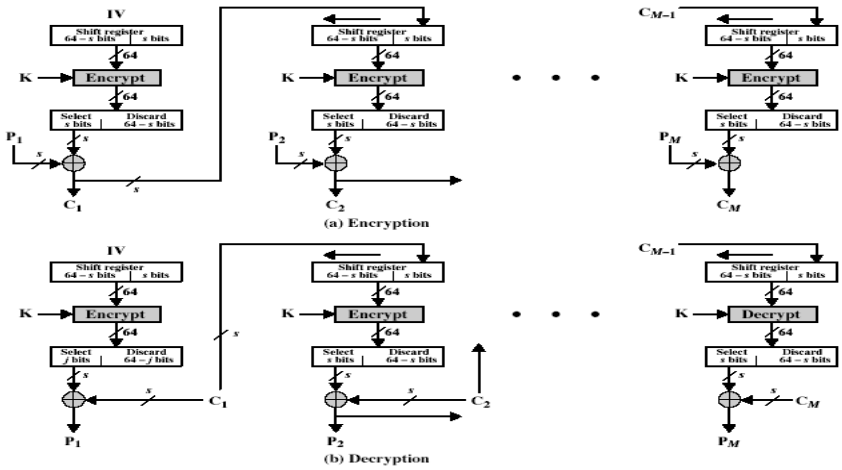
Cipher Feed Back (CFB)

- message is treated as a stream of bits
- added to the output of the block cipher
- result is feed back for next stage
- standard allows any number of bit (1, 8 or 64 or whatever) to be feed back
- 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 Feed Back (CFB)



Advantages/Limitations of CFB

- appropriate when data arrives in bits/bytes
- most common stream mode
- limitation is the need to stall while doing block encryption after every n-bits
- note that the block cipher is used in **encryption** mode at **both** ends
- errors propagate for several blocks after the error

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Output Feed Back (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

$C_i = P_i \text{ XOR } O_i$

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

$O_{-1} = IV$

- uses: stream encryption over noisy channels

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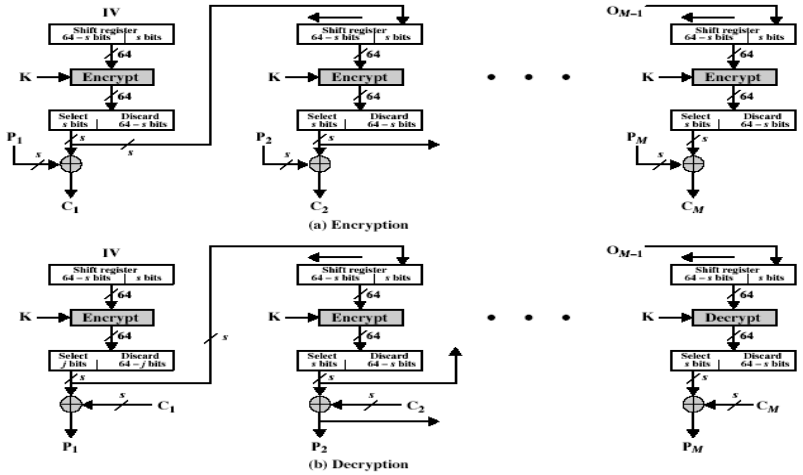
Output Feed Back (OFB)



Advantages/Limitations of OFB

- used when error feedback a problem or where need to do encryptions before message is available
- superficially similar to CFB
- but feedback is from the output of cipher and is independent of message
- must **never** reuse the same sequence (key + IV)
- sender and receiver must remain in sync, and some recovery method is needed to ensure this occurs

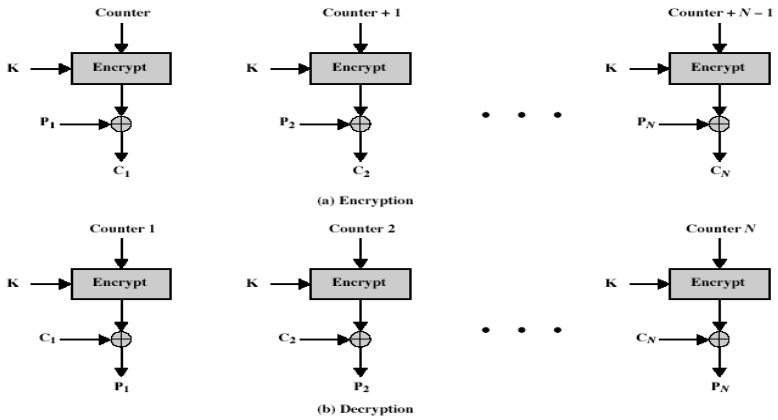
Counter (CTR)

- a "new" mode, though proposed early on
- similar to OFB but encrypts counter value rather than any feedback value
- must have a different key & 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/Limitations of CTR

- efficiency
  - can do parallel encryptions
  - in advance of need
  - good for high speed links
- random access to encrypted data blocks
- provable security (good as other modes)
- but must ensure never reuse key/counter values, otherwise could break (as OFB)

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New designs to replace DES

- International Data Encryption Algorithm
  - from Swiss Federal Institute of Technology (1990)
  - symmetric block cipher; 128 bit key
  - encrypts 64 bit blocks
  - uses three operations in contrast to DES and XOR
    - bitwise exclusive OR
    - addition of integer modulo 2^{16}
    - multiplication of integers modulo $2^{16} + 1$
- Blowfish
  - symmetric block cipher -- Bruce Schneier (1993)
  - can run in less than 5K of memory
  - variable key length (32 bits up to 448 bits)
  - uses 2 primitive operations:
    - addition (mod 2^{32}) & bitwise exclusive OR
  - operations performed on both halves each round
  - both sub-keys and S-boxes are produced by repeated applications of Blowfish itself

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DES Successor: origin of AES

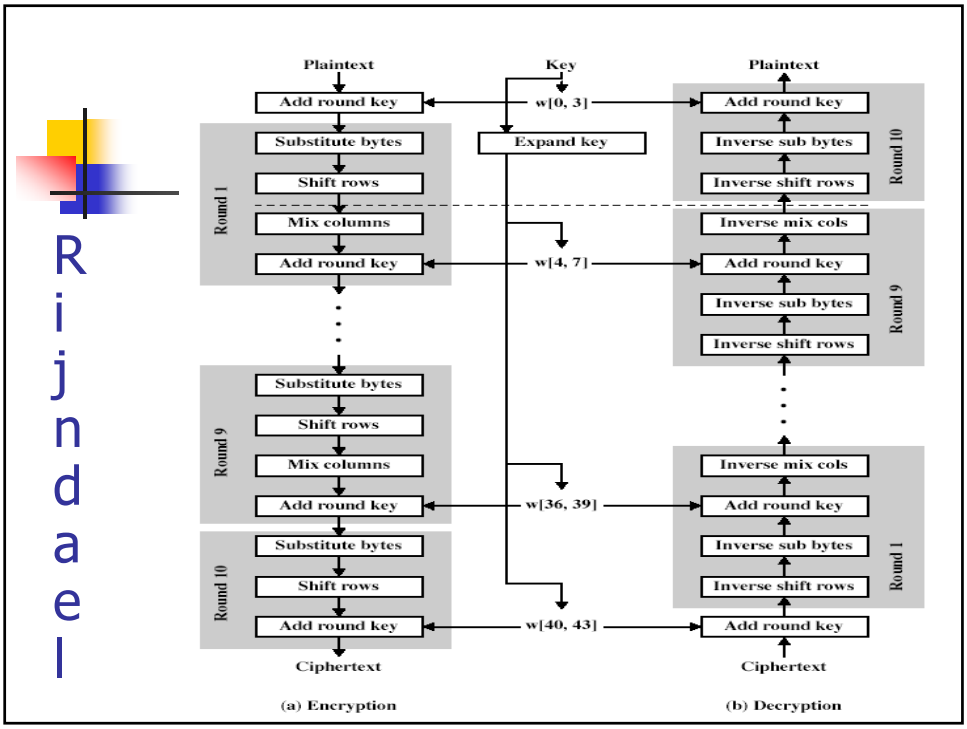
- National Institute of Standards and Technology (NIST) began the AES project in January 1997 to develop a Federal Information Processing standard (FIPS) for an encryption algorithm to protecting sensitive (unclassified) government information
- Issued a Call for Ciphers asking interested parties worldwide to submit encryption algorithms for review
- AES Requirements
  - private key symmetric block cipher
  - 128-bit data, 128/192/256-bit keys
  - stronger and faster than Triple-DES
  - active life of 20-30 years (+ archival use)
  - provide full specification and design details, royalty-free
  - both C and Java implementations
  - NIST have released all submissions and unclassified analyses

AES Evaluation Criteria

- initial criteria:
  - security – effort to practically cryptanalyze
  - cost – computational
  - algorithm & implementation characteristics
- final criteria
  - general security
  - software & hardware implementation ease
  - implementation attacks
  - flexibility (in en/decrypt, keying, other factors)
- after testing and evaluation, shortlist in Aug-99:
  - MARS (IBM) - complex, fast, high security margin
  - RC6 (USA) - v. simple, v. fast, low security margin
  - Rijndael (Belgium) - clean, fast, good security margin
  - Serpent (Euro) - slow, clean, v. high security margin
  - Twofish (USA) - complex, v. fast, high security margin
  - saw contrast between algorithms with
    - few complex rounds vs. many simple rounds
    - which refined existing ciphers verses new proposals

Rijndael designed by Rijmen-Daemen in Belgium

- has 128/192/256 bit keys
- 128 bit block size data
- operates an entire block in every round
- processes data as 4 groups of 4 bytes (state)
- has 9/11/13 rounds in which state undergoes:
  - byte substitution (1 S-box used on every byte)
  - shift rows (permute bytes between groups/columns)
  - mix columns (subs using matrix multiply of groups)
  - add round key (XOR state with key material)
- initial XOR key material and incomplete (no mix columns) one additional last round
- all operations can be combined into XOR and table lookups - hence very fast and efficient



AES Decryption

- AES decryption is not identical to encryption since steps done in reverse
- but can define an equivalent inverse cipher with steps as for encryption
  - but using inverses of each step
  - with a different key schedule
- works since result is unchanged when
  - swap byte substitution & shift rows
  - swap mix columns & add (tweaked) round key

Stream Ciphers

- Encryption scheme can change for each symbol of the plaintext
- Given
  - plaintext m1 m2 m3 … and keystream e1 e2 e3 …
  - ciphertext c1 c2 c3 … with ci = E(ei,mi); mi=D(ei,ci)
- In some sense, stream ciphers are block ciphers with block size of length 1
- Useful when plaintext needs to be processed one symbol at a time
- Most common approach
  To encrypt $c = p \oplus k$
  To decrypt $c \oplus k = (p \oplus k) \oplus k = p \oplus (k \oplus k) = p \oplus 0 = p$

Features to design into a stream cipher

- Long periods without repetition
- Depends on large enough key
- Functional complexity - each keystream bit should depend on most or all of the cryptovariable bits
- Statistically unpredictable
- Keystream should be statistically unbiased
- Advantages (disadv. for block)
  - Speed of transformation
  - No error propagation
- Disadvantages (adv. for block)
  - Low diffusion
  - Subject to malicious insertion and modification

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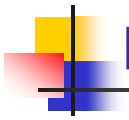

RC4

- a proprietary stream cipher owned by RSA DSI
- Ron Rivest design, simple but effective
- variable key size, byte-oriented operations
- widely used (web SSL/TLS, WEP)
- key forms random permutation of all 8-bit values; permutation used to scramble input info processed a byte at a time
- claimed secure against known attacks
  - have some analyses, none practical
- have a concern with WEP, but due to key handling rather than RC4 itself

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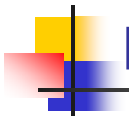
RC4 Key Schedule

- starts with an array S of numbers: 0..255
- use key to well and truly shuffle
- S forms **internal state** of the cipher
- given a key k of length n bytes

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

The input key k is no longer used.



RC4 Encryption

- encryption continues shuffling array values
- sum of shuffled pair selects "stream key" value
- XOR with next byte of message to en/decrypt

```
i, j = 0
for each message byte Mi
   i = (i + 1) mod 256;
   j = (j + S[i]) mod 256;
   swap(S[i], S[j]);
   t = (S[i] + S[j]) mod 256;
   Ci = Mi XOR S[t]
```