

# IS 2150 / TEL 2810

## Introduction to Security



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Lecture 7  
Oct 2, 2012

Basic Cryptography  
Network Security

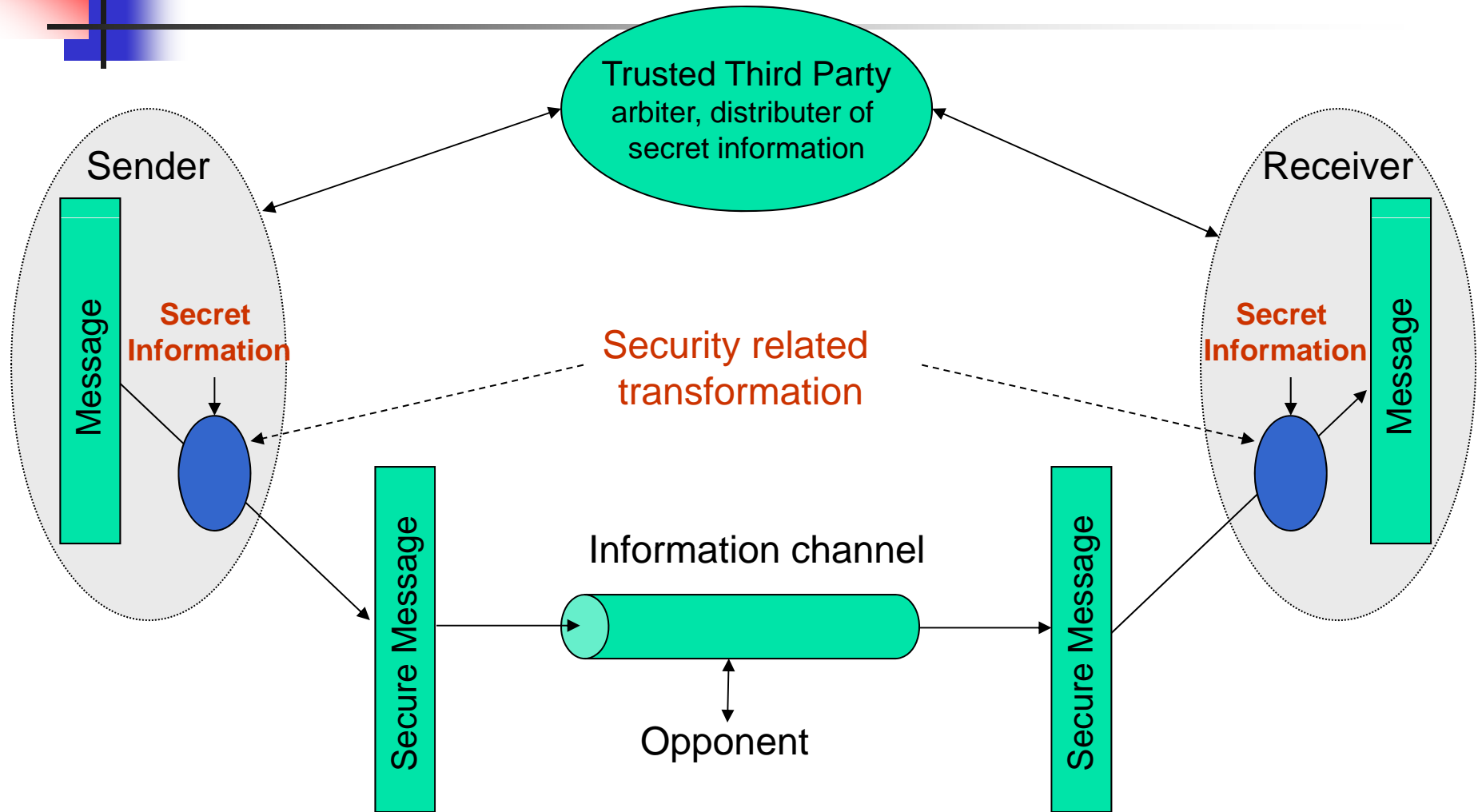


# Objectives

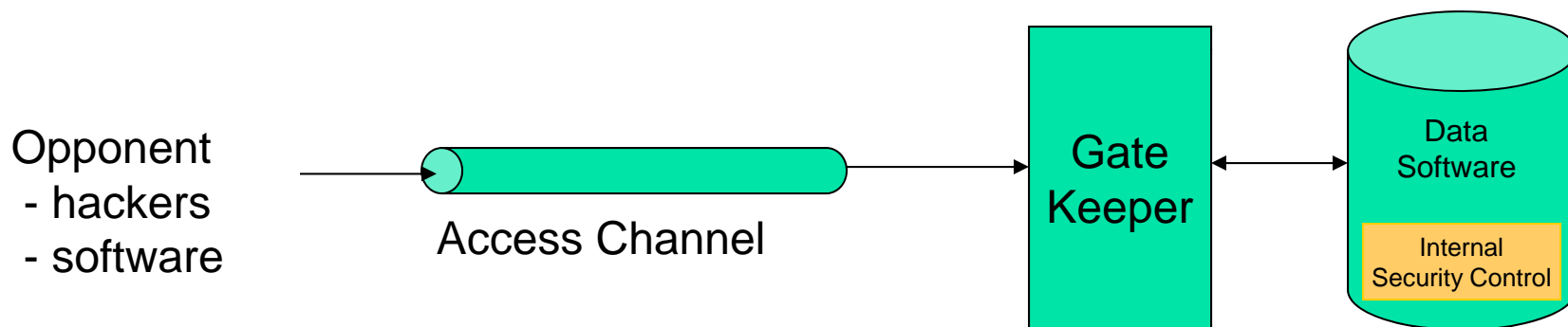
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- Understand/explain/employ the basic cryptographic techniques
  - Review the basic number theory used in cryptosystems
  - Classical system
  - Public-key system
  - Some crypto analysis
  - Message digest

# Secure Information Transmission (network security model)



# Security of Information Systems (Network access model)



Gatekeeper – firewall or equivalent, password-based login

Internal Security Control – Access control, Logs, audits, virus scans etc.

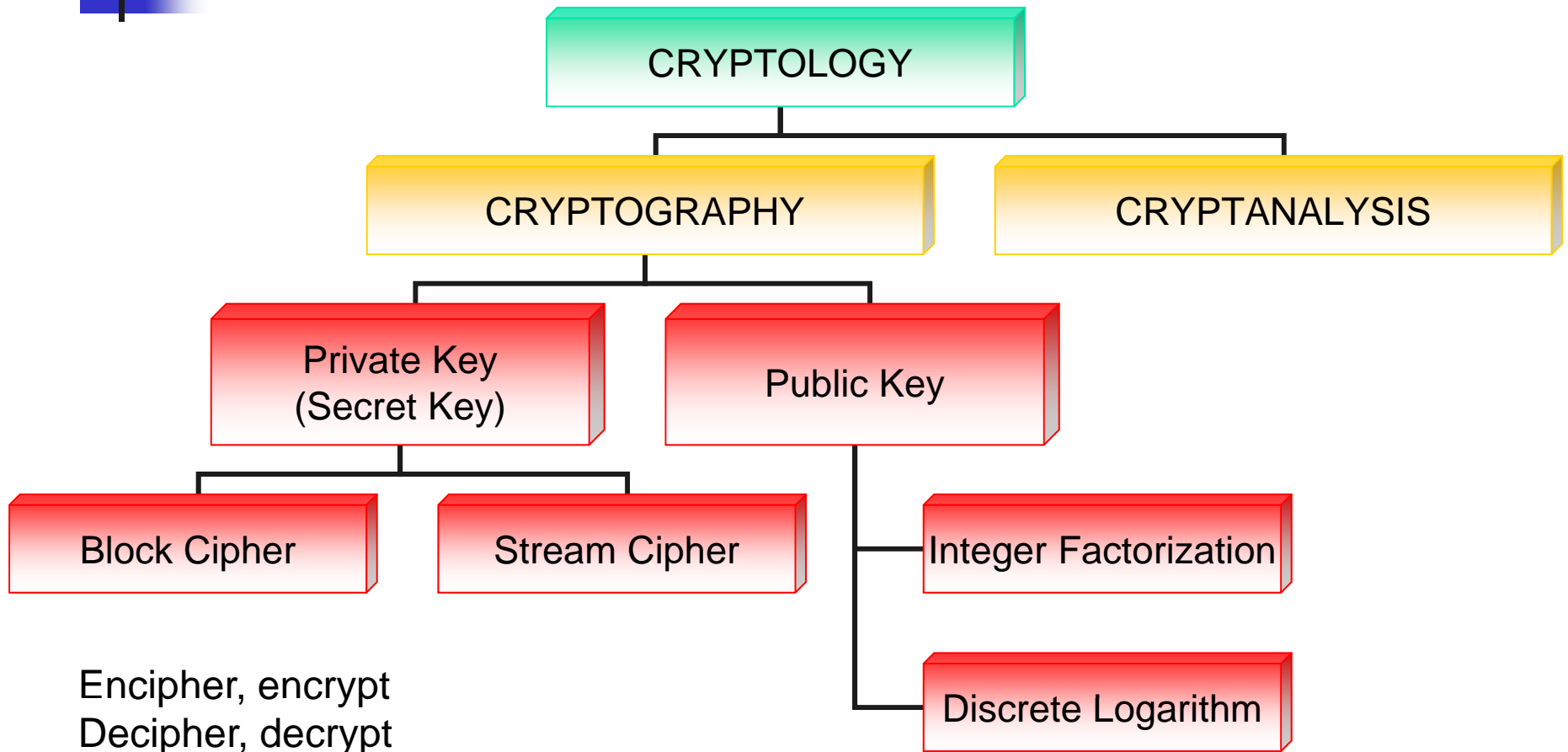


# Issues in Network security

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- Distribution of secret information to enable secure exchange of information
- Effect of communication protocols needs to be considered
- Encryption *if used cleverly and correctly*, can provide several of the security services
- Physical and logical placement of security mechanisms
- Countermeasures need to be considered

# Cryptology





# Elementary Number Theory

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- Natural numbers  $N = \{1, 2, 3, \dots\}$
- Whole numbers  $W = \{0, 1, 2, 3, \dots\}$
- Integers  $Z = \{\dots, -2, -1, 0, 1, 2, 3, \dots\}$
- Divisors
  - A number  $b$  is said to divide  $a$  if  $a = mb$  for some  $m$  where  $a, b, m \in Z$
  - We write this as  $b \mid a$



# Divisors

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- Some common properties
  - If  $a \mid 1$ ,  $a = +1$  or  $-1$
  - If  $a \mid b$  and  $b \mid a$  then  $a = +b$  or  $-b$
  - Any  $b \in \mathbb{Z}$  divides 0 if  $b \neq 0$
  - If  $b \mid g$  and  $b \mid h$  then  $b \mid (mg + nh)$  where  $b, m, n, g, h \in \mathbb{Z}$
- Examples:
  - The positive divisors of 42 are ?
  - $3 \mid 6$  and  $3 \mid 21 \Rightarrow 3 \mid 21m + 6n$  for  $m, n \in \mathbb{Z}$





# Prime Numbers

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- An integer  $p$  is said to be a prime number if its only positive divisors are 1 and itself
  - 2, 3, 7, 11, ..
- Any integer can be expressed as a *unique* product of prime numbers raised to positive integral powers
- Examples
  - $7569 = 3 \times 3 \times 29 \times 29 = 3^2 \times 29^2$
  - $5886 = 2 \times 27 \times 109 = 2 \times 3^3 \times 109$
  - $4900 = 7^2 \times 5^2 \times 2^2$
  - $100 = ?$
  - $250 = ?$
- This process is called *Prime Factorization*



# Greatest common divisor (GCD)

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- Definition: Greatest Common Divisor
  - This is the largest divisor of *both*  $a$  and  $b$
- Given two integers  $a$  and  $b$ , the positive integer  $c$  is called their GCD or greatest common divisor if and only if
  - $c \mid a$  and  $c \mid b$
  - Any divisor of both  $a$  and  $b$  also divides  $c$
- Notation:  $\gcd(a, b) = c$
- Example:  $\gcd(49, 63) = ?$



# Relatively Prime Numbers

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- Two numbers are said to be relatively prime if their gcd is 1
  - Example: 63 and 22 are relatively prime
- How do you determine if two numbers are relatively prime?
  - Find their GCD or
  - Find their prime factors
    - If they do not have a common prime factor other than 1, they are relatively prime
  - Example:  $63 = 9 \times 7 = 3^2 \times 7$  and  $22 = 11 \times 2$



# The modulo operation

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- What is  $27 \bmod 5$ ?
- Definition
  - Let  $a, r, m$  be integers and let  $m > 0$
  - We write  $a \equiv r \pmod{m}$  if  $m$  divides  $r - a$  (or  $a - r$ ) and  $0 \leq r < m$
  - $m$  is called ?
  - $r$  is called ?
  - Note:  $a = m \cdot q + r$  ; what is  $q$  ?



# Modular Arithmetic

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- We say that  $a \equiv b \pmod{m}$  if  $m \mid a - b$ 
  - Read as:  $a$  is congruent to  $b$  modulo  $m$
  - $m$  is called the modulus
  - Example:  $27 \equiv 2 \pmod{5}$
  - Example:  $27 \equiv 7 \pmod{5}$  and  $7 \equiv 2 \pmod{5}$
- $a \equiv b \pmod{m} \Rightarrow b \equiv a \pmod{m}$ 
  - Example:  $2 \equiv 27 \pmod{5}$
- We usually consider the *smallest positive remainder* which is called the **residue**



# Modulo Operation

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- The modulo operation “reduces” the infinite set of integers to a finite set
- Example: modulo 5 operation
  - We have five sets
    - $\{\dots, -10, -5, 0, 5, 10, \dots\} \Rightarrow a \equiv 0 \pmod{5}$
    - $\{\dots, -9, -4, 1, 6, 11, \dots\} \Rightarrow a \equiv 1 \pmod{5}$
    - $\{\dots, -8, -3, 2, 7, 12, \dots\} \Rightarrow a \equiv 2 \pmod{5}$ , etc.
  - The set of residues of integers modulo 5 has five elements  $\{0, 1, 2, 3, 4\}$  and is denoted  $Z_5$ .



# Modulo Operation

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- Properties

- $[(a \bmod n) + (b \bmod n)] \bmod n = (a + b) \bmod n$
- $[(a \bmod n) - (b \bmod n)] \bmod n = (a - b) \bmod n$
- $[(a \bmod n) \times (b \bmod n)] \bmod n = (a \times b) \bmod n$
- $(-1) \bmod n = n - 1$ 
  - (Using  $b = q.n + r$ , with  $b = -1$ ,  $q = -1$  and  $r = n-1$ )



# Brief History

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- All encryption algorithms from BC till 1976 were secret key algorithms
  - Also called private key algorithms or symmetric key algorithms
  - Julius Caesar used a substitution cipher
  - Widespread use in World War II (enigma)
- Public key algorithms were introduced in 1976 by Whitfield Diffie and Martin Hellman





# Cryptosystem

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- $(\mathcal{E}, \mathcal{D}, \mathcal{M}, \mathcal{K}, \mathcal{C})$ 
  - $\mathcal{E}$  set of encryption functions  
 $e: \mathcal{M} \times \mathcal{K} \rightarrow \mathcal{C}$
  - $\mathcal{D}$  set of decryption functions  
 $d: \mathcal{C} \times \mathcal{K} \rightarrow \mathcal{M}$
  - $\mathcal{M}$  set of plaintexts
  - $\mathcal{K}$  set of keys
  - $\mathcal{C}$  set of ciphertexts



# Example

---

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



# Cæsar cipher

- Let  $k = 9$ ,  $m = \text{"VELVET"} (21\ 4\ 11\ 21\ 4\ 19)$ 
  - $E_k(m) = (30\ 13\ 20\ 30\ 13\ 28) \bmod 26$   
 $= \text{"4\ 13\ 20\ 4\ 13\ 2"} = \text{"ENUENC"}$
  - $D_k(m) = (26 + c - k) \bmod 26$   
 $= (21\ 30\ 37\ 21\ 30\ 19) \bmod 26$   
 $= \text{"21\ 4\ 11\ 21\ 4\ 19"} = \text{"VELVET"}$

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

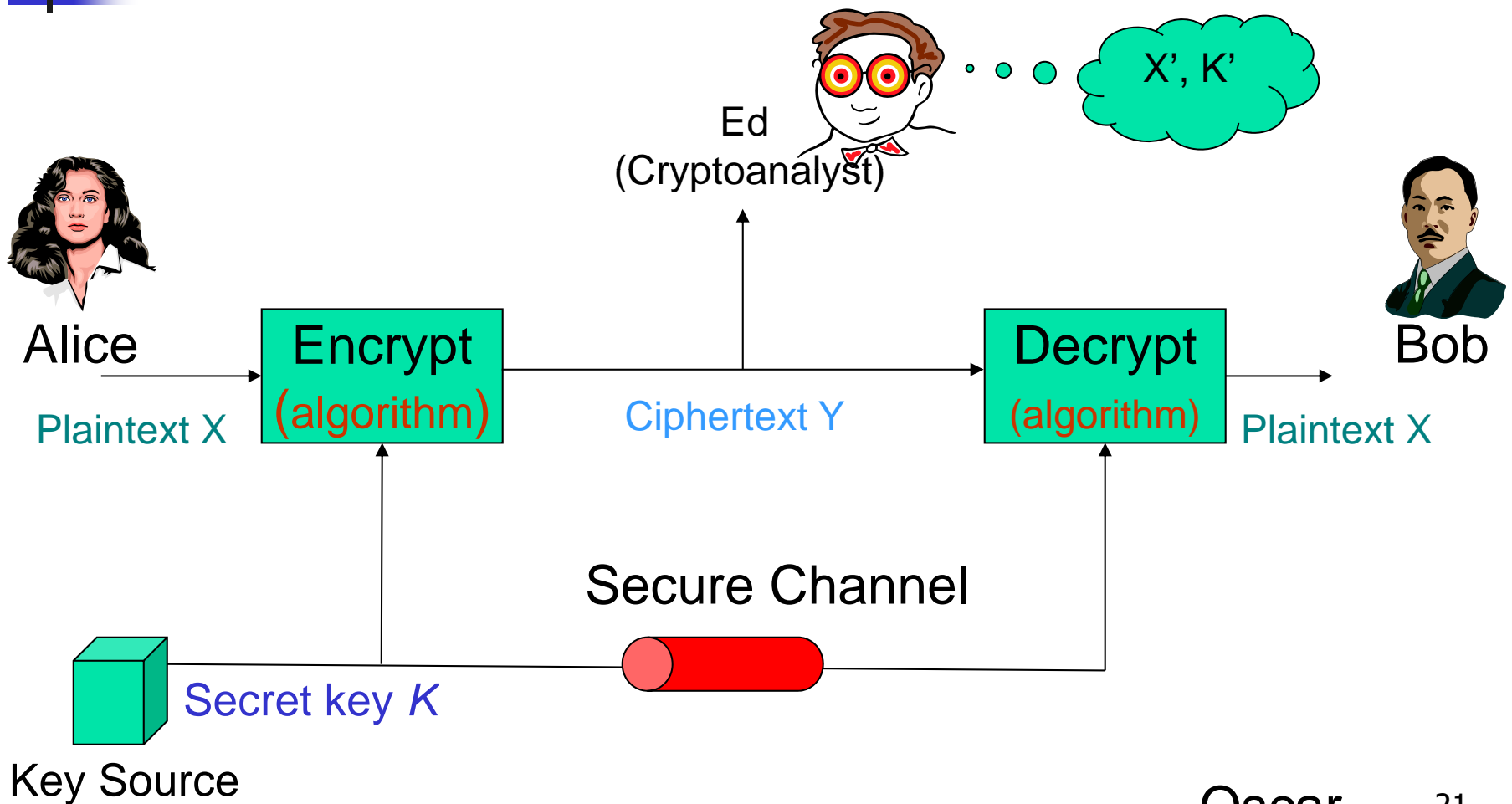


# Attacks

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- *Ciphertext only:*
  - adversary has only  $Y$ ;
  - goal ?
- *Known plaintext:*
  - adversary has  $X, Y$ ;
  - goal ?
- *Chosen plaintext:*
  - adversary gets a specific plaintext enciphered;
  - goal ?

# Classical Cryptography





# Classical Cryptography

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- Sender, receiver share common key
  - Keys may be the same, or trivial to derive from one another
  - Sometimes called *symmetric cryptography*
- Two basic types
  - Transposition ciphers
  - Substitution ciphers
- Product ciphers
  - Combinations of the two basic types



# Classical Cryptography

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- $y = E_k(x)$  : Ciphertext  $\rightarrow$  Encryption
- $x = D_k(y)$  : Plaintext  $\rightarrow$  Decryption
- $k$  = encryption and decryption key
- The functions  $E_k()$  and  $D_k()$  must be inverses of one another
  - $E_k(D_k(y)) = ?$
  - $D_k(E_k(x)) = ?$
  - $E_k(D_k(x)) = ?$



# Transposition Cipher

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- Rearrange letters in plaintext to produce ciphertext
- Example (Rail-Fence Cipher)
  - Plaintext is "HELLO WORLD"
  - Rearrange as
    - HLOOL
    - ELWRD
  - Ciphertext is HLOOL ELWRD





# Attacking the Cipher

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- Anagramming
  - If 1-gram frequencies match English frequencies, but other  $n$ -gram frequencies do not, probably transposition
  - Rearrange letters to form  $n$ -grams with highest frequencies



# Example

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- Ciphertext: HLOOLELWRD
- Frequencies of 2-grams beginning with H
  - HE 0.0305
  - HO 0.0043
  - HL, HW, HR, HD  $< 0.0010$
- Frequencies of 2-grams ending in H
  - WH 0.0026
  - EH, LH, OH, RH, DH  $\leq 0.0002$
- Implies E follows H



# Example

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- Arrange so that H and E are adjacent

HE

LL

OW

OR

LD

- Read off across, then down, to get original plaintext



# Substitution Ciphers

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- Change characters in plaintext to produce ciphertext
- Example (Cæsar cipher)
  - Plaintext is HELLO WORLD;
  - Key is 3, usually written as letter 'D'
  - Ciphertext is KHOOR ZRUOG



# Attacking the Cipher

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- Brute Force: Exhaustive search
  - If the key space is small enough, try all possible keys until you find the right one
  - Cæsar cipher has 26 possible keys
- Statistical analysis
  - Compare to 1-gram model of English



# Statistical Attack

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- Ciphertext is KHOOR ZRUOG
- Compute frequency of each letter in ciphertext:

G	0.1	H	0.1	K	0.1	O	0.3
R	0.2	U	0.1	Z	0.1		
- Apply 1-gram model of English
  - Frequency of characters (1-grams) in English is on next slide

# Character Frequencies (Denning)

a	0.080	h	0.060	n	0.070	t	0.090
b	0.015	i	0.065	o	0.080	u	0.030
c	0.030	j	0.005	p	0.020	v	0.010
d	0.040	k	0.005	q	0.002	w	0.015
e	0.130	l	0.035	r	0.065	x	0.005
f	0.020	m	0.030	s	0.060	y	0.020
g	0.015					z	0.002



# Statistical Analysis

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- $f(c)$  frequency of character  $c$  in ciphertext
- $\varphi(i)$ :
  - correlation of frequency of letters in ciphertext with corresponding letters in English, assuming key is  $i$
  - $\varphi(i) = \sum_{0 \leq c \leq 25} f(c)p(c-i)$
  - so here,  
$$\varphi(i) = 0.1p(6-i) + 0.1p(7-i) + 0.1p(10-i) + 0.3p(14-i) + 0.2p(17-i) + 0.1p(20-i) + 0.1p(25-i)$$
    - $p(x)$  is frequency of character  $x$  in English
  - Look for maximum correlation!



# Correlation: $\varphi(i)$ for $0 \leq i \leq 25$

$i$	$\varphi(i)$	$i$	$\varphi(i)$	$i$	$\varphi(i)$	$i$	$\varphi(i)$
0	0.0482	7	0.0442	13	0.0520	19	0.0315
1	0.0364	8	0.0202	14	0.0535	20	0.0302
2	0.0410	9	0.0267	15	0.0226	21	0.0517
3	0.0575	10	0.0635	16	0.0322	22	0.0380
4	0.0252	11	0.0262	17	0.0392	23	0.0370
5	0.0190	12	0.0325	18	0.0299	24	0.0316
6	0.0660					25	0.0430



# The Result

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- Ciphertext is KHOOR ZRUOG
- Most probable keys, based on  $\varphi$ :
  - $i = 6, \varphi(i) = 0.0660$ 
    - plaintext EBIIL TLOLA (How?)
  - $i = 10, \varphi(i) = 0.0635$ 
    - plaintext AXEEH PHKEW (How?)
  - $i = 3, \varphi(i) = 0.0575$ 
    - plaintext HELLO WORLD (How?)
  - $i = 14, \varphi(i) = 0.0535$ 
    - plaintext WTAAD LDGAS
- Only English phrase is for  $i = 3$ 
  - That's the key (3 or 'D')



# Cæsar's Problem

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- Key is too short
  - Can be found by exhaustive search
  - Statistical frequencies not concealed well
    - They look too much like regular English letters
- So make it longer
  - Multiple letters in key
  - Idea is to smooth the statistical frequencies to make cryptanalysis harder



# Vigenère Cipher

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- Like Cæsar cipher, but use a phrase
- Example
  - Message THE BOY HAS THE BALL
  - Key VIG
  - Encipher using Cæsar cipher for each letter:

key	VIGVIGVIGVIGVIGV
plain	THEBOYHASTHEBALL
cipher	OPKWWECIYOPKWIRG



# Relevant Parts of Tableau

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	<i>G</i>	<i>I</i>	<i>V</i>
<i>A</i>	<i>G</i>	<i>I</i>	<i>V</i>
<i>B</i>	<i>H</i>	<i>J</i>	<i>W</i>
<i>E</i>	<i>K</i>	<i>M</i>	<i>Z</i>
<i>H</i>	<i>N</i>	<i>P</i>	<i>C</i>
<i>L</i>	<i>R</i>	<i>T</i>	<i>G</i>
<i>O</i>	<i>U</i>	<i>W</i>	<i>J</i>
<i>S</i>	<i>Y</i>	<i>A</i>	<i>N</i>
<i>T</i>	<i>Z</i>	<i>B</i>	<i>O</i>
<i>Y</i>	<i>E</i>	<i>H</i>	<i>T</i>

- Tableau with relevant rows, columns only
- Example encipherments:
  - key *V*, letter *T*: follow *V* column down to *T* row (giving "O")
  - Key *I*, letter *H*: follow *I* column down to *H* row (giving "P")



# Useful Terms

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- *period*: length of key
  - In earlier example, period is 3
- *tableau*: table used to encipher and decipher
  - Vigènere cipher has key letters on top, plaintext letters on the left
- *polyalphabetic*: the key has several different letters
  - Cæsar cipher is monoalphabetic

# Attacking the Cipher

- Key to attacking vigenère cipher
  - determine the key length
  - If the keyword is  $n$ , then the cipher consists of  $n$  monoalphabetic substitution ciphers

key	VIGVIGVIGVIGVIGV
plain	THEBOYHASTHEBALL
cipher	O [redacted] PKWIRG

key	DECEPTIVEDECEPTIVEDECEPTIVE
plain	WEAREDISCOVEREDSAVEYOURSELF
cipher	ZICV [redacted] TWAVZHCQYGLMGJ



# One-Time Pad

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- A Vigenère cipher with a random key at least as long as the message
  - Provably unbreakable; Why?
  - Consider ciphertext `DXQR`. Equally likely to correspond to
    - plaintext `DOIT` (key `AJIY`) and
    - plaintext `DONT` (key `AJDY`) and any other 4 letters
  - Warning: keys *must* be random, or you can attack the cipher by trying to regenerate the key



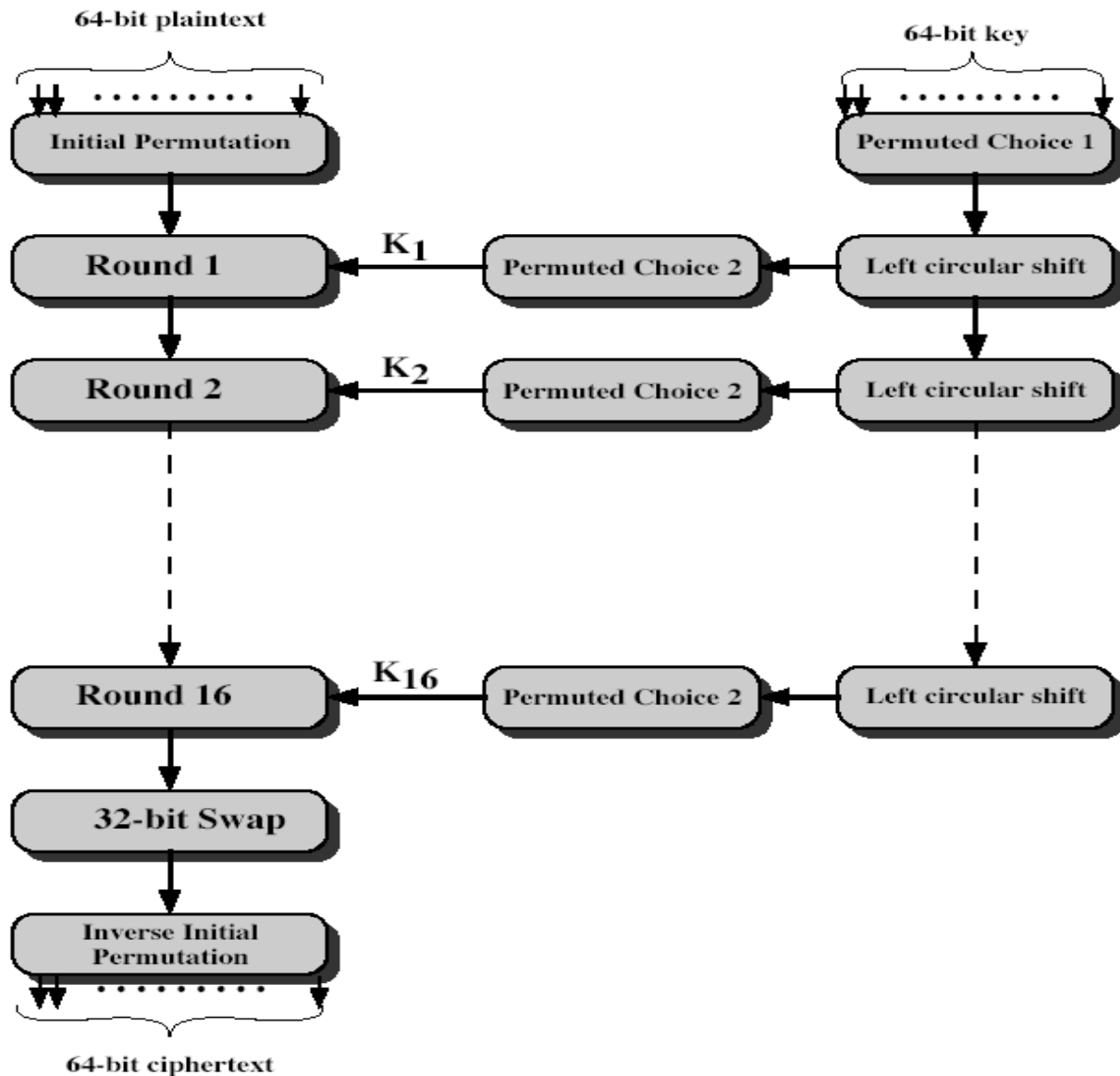


# Overview of the DES

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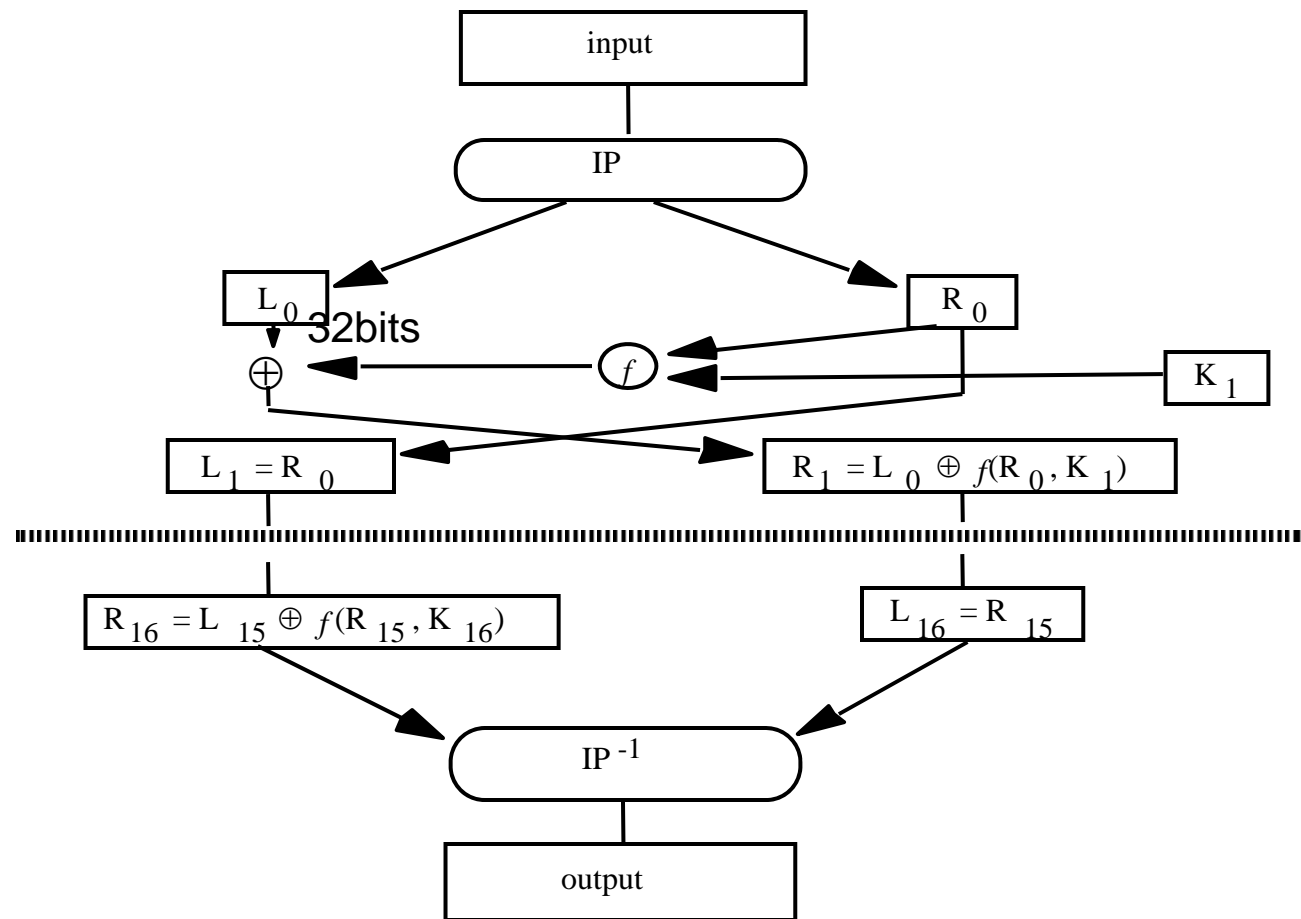
- A block cipher:
  - encrypts blocks of 64 bits using a 64 bit key
  - outputs 64 bits of ciphertext
  - A **product cipher**
    - performs both substitution and transposition (permutation) on the bits
  - basic unit is the bit
- Cipher consists of 16 rounds (iterations) each with a round key generated from the user-supplied key

# DES

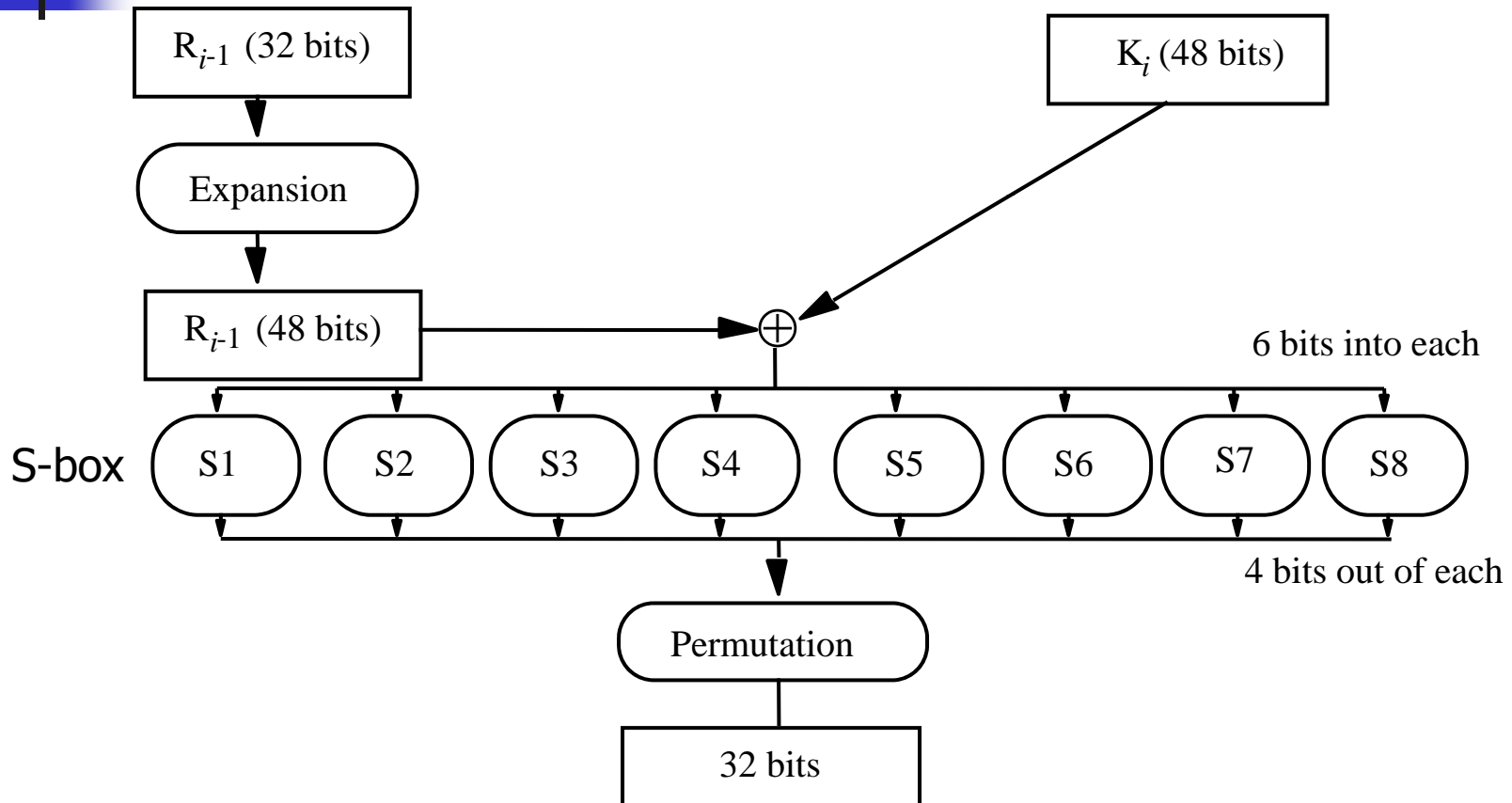


- Round keys are 48 bits each
  - Extracted from 64 bits
  - Permutation applied
- Deciphering involves using round keys in reverse

# Encipherment



# The $f$ Function





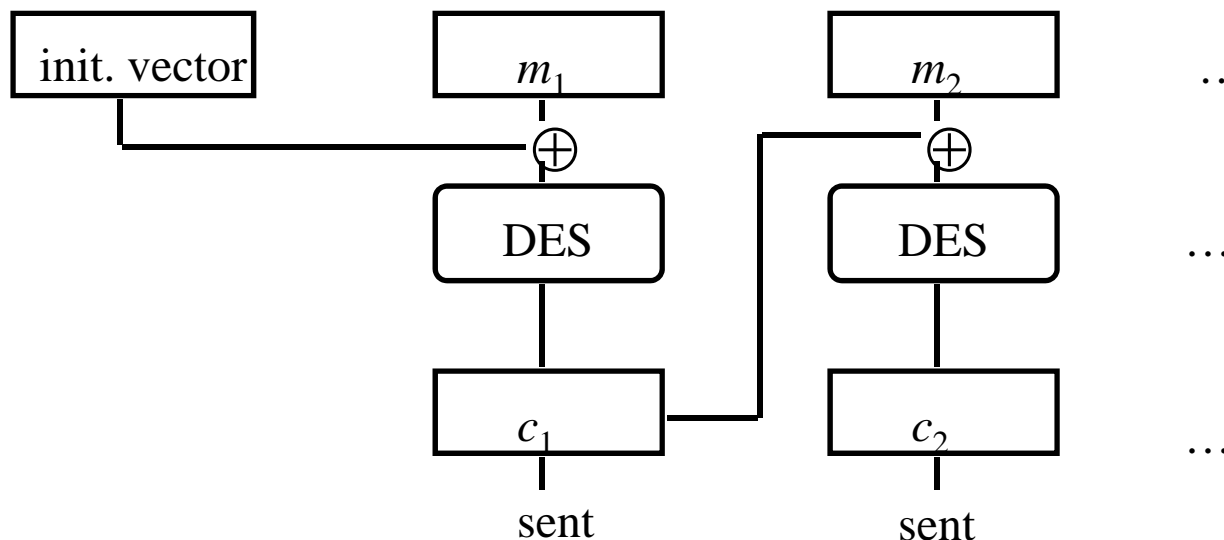
# Controversy

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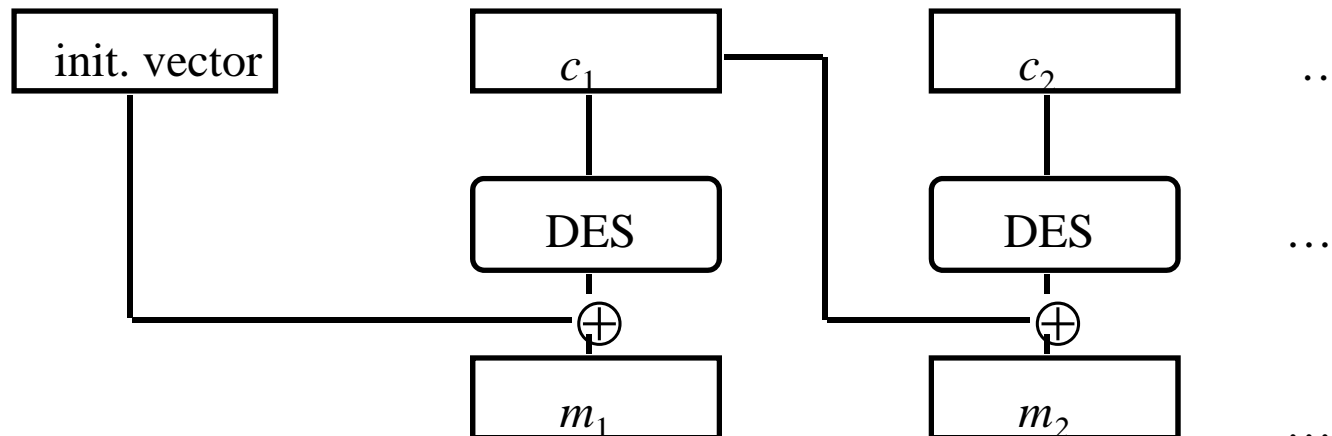
- Considered too weak
  - Design to break it using 1999 technology published
  - Design decisions not public
    - S-boxes may have backdoors
- Several other weaknesses found
  - Mainly related to keys

# DES Modes

- Electronic Code Book Mode (ECB):
  - Encipher each block independently
- Cipher Block Chaining Mode (CBC)
  - XOR each block with previous ciphertext block
  - Uses an initialization vector for the first one



# CBC Mode Decryption



- CBC has self healing property
  - If one block of ciphertext is altered, the error propagates for at most two blocks




# Self-Healing Property

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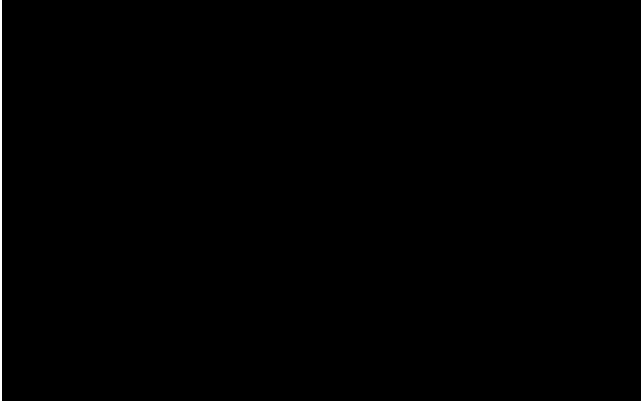
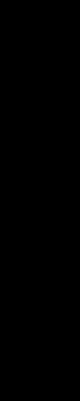
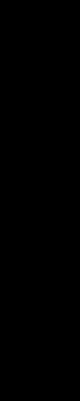
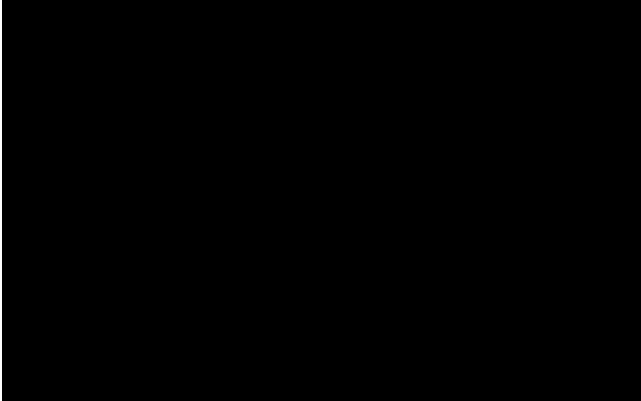
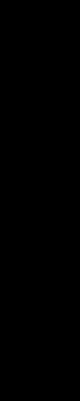
- Initial message

- 3231343336353837 3231343336353837  
3231343336353837 3231343336353837

- Received as (underlined 4c should be 4b)

- ef7c  b2b4ce6f3b f6266e3a97af0e2c  
746ab9a6308f4256 33e60b451b09603d

- Which decrypts to

-  3231  3336353837  
3231  3336353837
  -  ined; p  ntext "heals"





# Public Key Cryptography

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- Two keys
  - *Private key* known only to individual
  - *Public key* available to anyone
- Idea
  - Confidentiality:
    - encipher using public key,
    - decipher using private key
  - Integrity/authentication:
    - encipher using private key,
    - decipher using public one



# Requirements

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1. Given the appropriate key, it must be computationally easy to encipher or decipher a message
2. It must be computationally infeasible to derive the private key from the public key
3. It must be computationally infeasible to determine the private key from a chosen plaintext attack



# Diffie-Hellman

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- Compute a common, shared key
  - Called a *symmetric key exchange protocol*
- Based on discrete logarithm problem
  - Given integers  $n$  and  $g$  and prime number  $p$ , compute  $k$  such that  $n = g^k \bmod p$
  - Solutions known for small  $p$
  - Solutions computationally infeasible as  $p$  grows large – hence, choose large  $p$



# Algorithm

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- Constants known to participants
  - prime  $p$ ; integer  $g$  other than 0, 1 or  $p-1$
- Alice: (private =  $k_A$ , public =  $K_A$ )
- Bob: (private =  $k_B$ , public =  $K_B$ )
  - $K_A = g^{k_A} \text{ mod } p$
  - $K_B = g^{k_B} \text{ mod } p$
- To communicate with Bob,
  - Alice computes  $S_{A,B} = K_B^{k_A} \text{ mod } p$
- To communicate with Alice,
  - Bob computes  $S_{B,A} = K_A^{k_B} \text{ mod } p$
- $S_{A,B} = S_{B,A} ?$



# Example

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- Assume  $p = 53$  and  $g = 17$
- Alice chooses  $k_A = 5$ 
  - Then  $K_A = 17^5 \bmod 53 = 40$
- Bob chooses  $k_B = 7$ 
  - Then  $K_B = 17^7 \bmod 53 = 6$
- Shared key:
  - $K_B^{k_A} \bmod p = 6^5 \bmod 53 = 38$
  - $K_A^{k_B} \bmod p = 40^7 \bmod 53 = 38$

Exercise:

Let  $p = 5$ ,  $g = 3$   
 $k_A = 4$ ,  $k_B = 3$

$K_A = ?$ ,  $K_B = ?$ ,  
 $S = ?$ ,



# RSA

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- Relies on the difficulty of determining the number of numbers relatively prime to a large integer  $n$
- **Totient** function  $\phi(n)$ 
  - Number of + integers less than  $n$  and relatively prime to  $n$
- Example:  $\phi(10) = 4$ 
  - What are the numbers relatively prime to 10?
- $\phi(77)$  ?
- $\phi(p)$  ? When  $p$  is a prime number
- $\phi(pq)$  ? When  $p$  and  $q$  are prime numbers

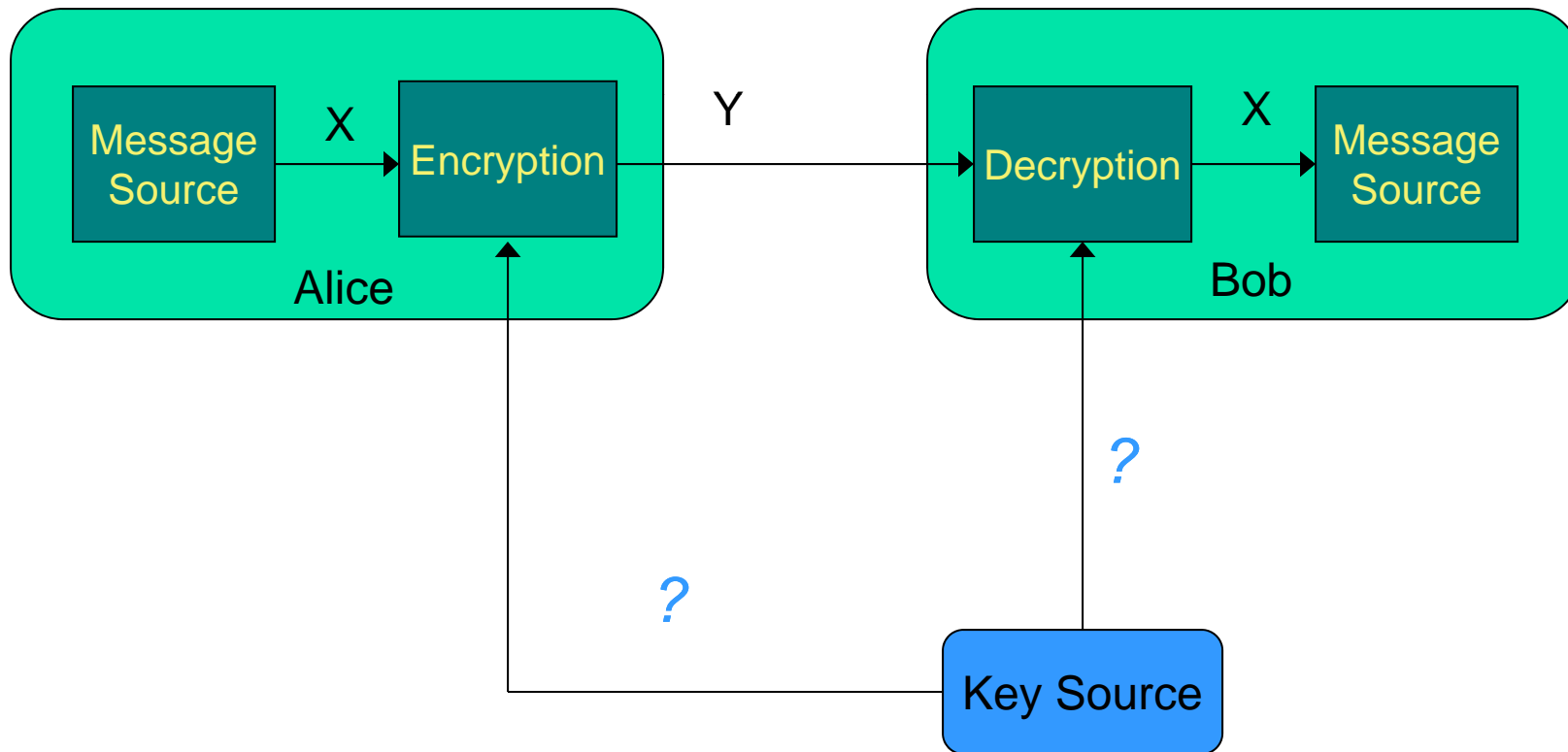


# Algorithm

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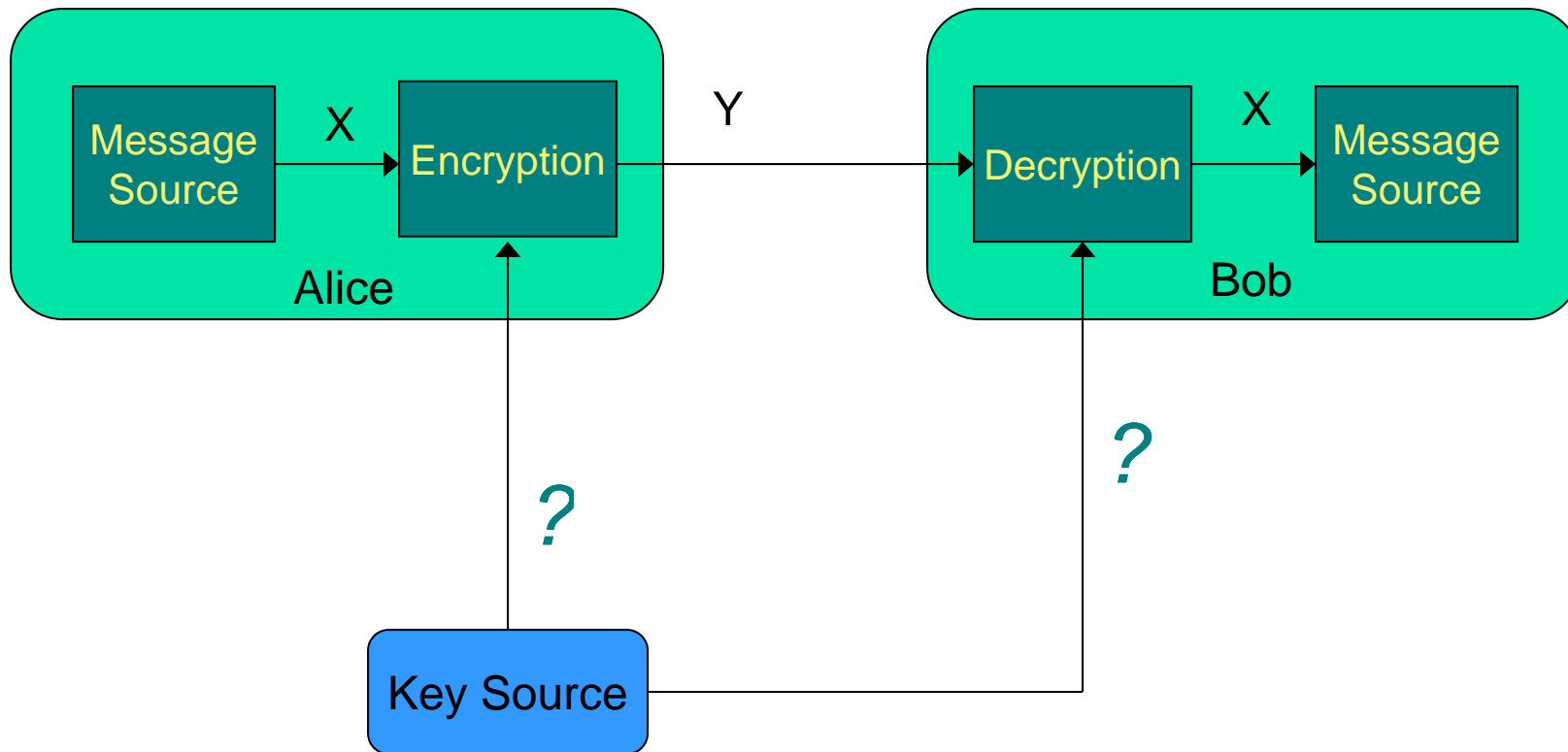
- Choose two large prime numbers  $p, q$ 
  - Let  $n = pq$ ; then  $\phi(n) = (p-1)(q-1)$
  - Choose  $e < n$  relatively prime to  $\phi(n)$ .
  - Compute  $d$  such that  $ed \bmod \phi(n) = 1$ 
    - Public key:  $(e, n)$ ;
    - private key:  $d$  (or  $(d, n)$ )
- Encipher:  $c = m^e \bmod n$
- Decipher:  $m = c^d \bmod n$

# Confidentiality using RSA

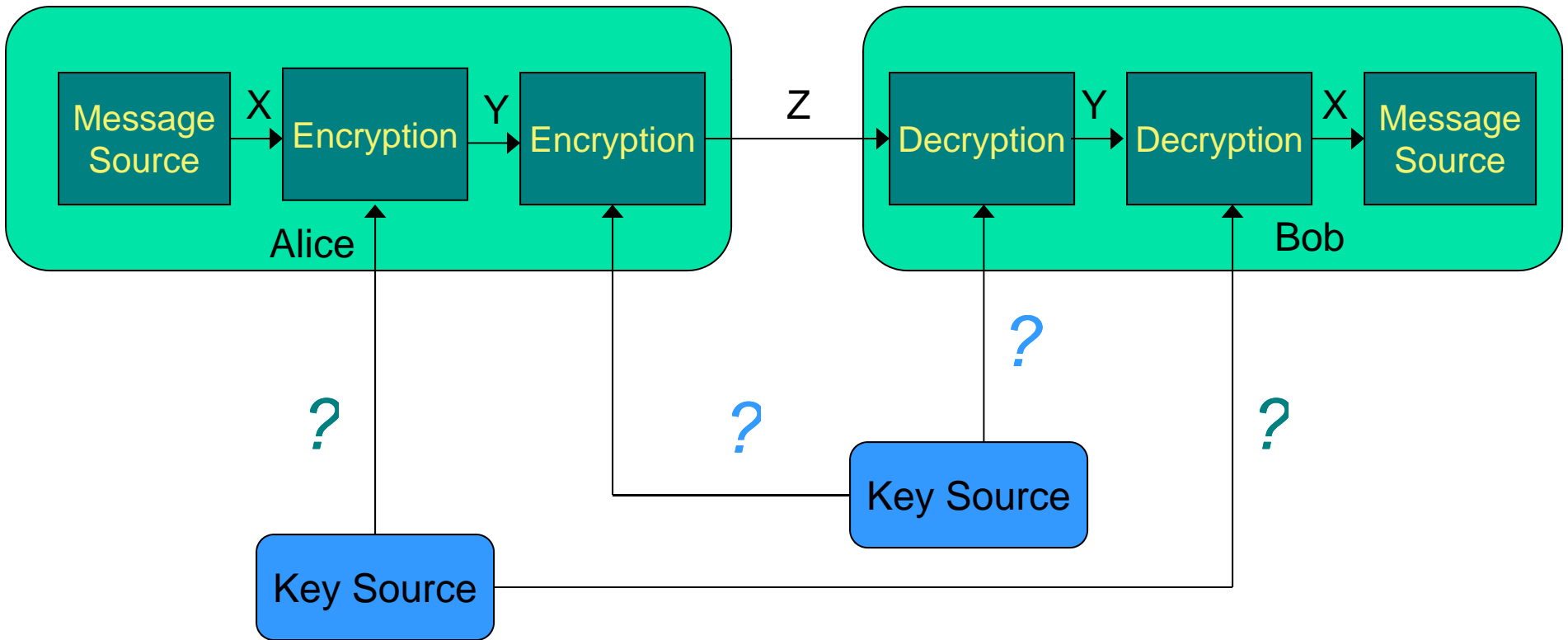
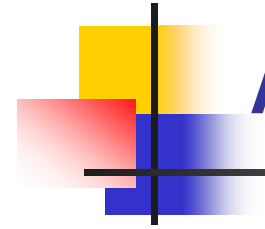




# Authentication using RSA



# Confidentiality + Authentication





# Warnings

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- Encipher message in blocks considerably larger than the examples here
  - If 1 character per block, RSA can be broken using statistical attacks (just like classical cryptosystems)
  - Attacker cannot alter letters, but can rearrange them and alter message meaning
    - Example: reverse enciphered message: ON to get NO



# Cryptographic Checksums

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- Mathematical function to generate a set of  $k$  bits from a set of  $n$  bits (where  $k \leq n$ ).
  - $k$  is smaller than  $n$  except in unusual circumstances
  - Keyed CC: requires a cryptographic key
$$h = C_{key}(M)$$
  - Keyless CC: requires no cryptographic key
    - Message Digest or One-way Hash Functions
$$h = H(M)$$
- Can be used for message authentication
  - Hence, also called Message Authentication Code (MAC)



# Mathematical characteristics

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- Every bit of the message digest function potentially influenced by every bit of the function's input
- If any given bit of the function's input is changed, every output bit has a 50 percent chance of changing
- Given an input file and its corresponding message digest, it should be computationally infeasible to find another file with the same message digest value



# Definition

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- Cryptographic checksum function  $h: A \rightarrow B$ :
  1. For any  $x \in A$ ,  $h(x)$  is easy to compute
    - Makes hardware/software implementation easy
  2. For any  $y \in B$ , it is computationally infeasible to find  $x \in A$  such that  $h(x) = y$ 
    - *One-way property*
  3. It is computationally infeasible to find  $x, x' \in A$  such that  $x \neq x'$  and  $h(x) = h(x')$
  4. Alternate form: Given any  $x \in A$ , it is computationally infeasible to find a different  $x' \in A$  such that  $h(x) = h(x')$ .



# Collisions

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- If  $x \neq x'$  and  $h(x) = h(x')$ ,  $x$  and  $x'$  are a collision
  - Pigeonhole principle: if there are  $n$  containers for  $n+1$  objects, then at least one container will have 2 objects in it.
  - Application: suppose  $n = 5$  and  $k = 3$ . Then there are 32 elements of A and 8 elements of B, so
    - each element of B has at least 4 corresponding elements of A



# Keys

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- Keyed cryptographic checksum:  
requires cryptographic key
  - DES in chaining mode: encipher message, use last  $n$  bits. Requires a key to encipher, so it is a keyed cryptographic checksum.
- Keyless cryptographic checksum:  
requires no cryptographic key
  - MD5 and SHA-1 are best known; others include MD4, HAVAL, and Snefru





# Message Digest

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- MD2, MD4, MD5 (Ronald Rivest)
  - Produces 128-bit digest;
  - MD2 is probably the most secure, longest to compute (hence rarely used)
  - MD4 is a fast alternative; MD5 is modification of MD4
- SHA, SHA-1 (Secure Hash Algorithm)
  - Related to MD4; used by NIST's Digital Signature
  - Produces 160-bit digest
  - SHA-1 may be better
- SHA-256, SHA-384, SHA-512
  - 256-, 384-, 512 hash functions designed to be use with the Advanced Encryption Standards (AES)
- Example:
  - MD5(There is \$1500 in the blue bo) = f80b3fde8ecbac1b515960b9058de7a1
  - MD5(There is \$1500 in the blue box) = a4a5471a0e019a4a502134d38fb64729

# Hash Message Authentication Code (HMAC)

- Make keyed cryptographic checksums from keyless cryptographic checksums
- $h$  be keyless cryptographic checksum function that takes data in blocks of  $b$  bytes and outputs blocks of  $l$  bytes.  $k'$  is cryptographic key of length  $b$  bytes (from  $k$ )
  - If short, pad with 0s' to make  $b$  bytes; if long, hash to length  $b$
- *ipad* is 00110110 repeated  $b$  times
- *opad* is 01011100 repeated  $b$  times
- $\text{HMAC-}h(k, m) = h(k' \oplus \text{opad} || h(k' \oplus \text{ipad} || m))$ 
  - $\oplus$  exclusive or,  $||$  concatenation



# Protection Strength

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- Unconditionally Secure
  - Unlimited resources + unlimited time
  - Still the plaintext CANNOT be recovered from the ciphertext
- Computationally Secure
  - Cost of breaking a ciphertext exceeds the value of the hidden information
  - The time taken to break the ciphertext exceeds the useful lifetime of the information

# Average time required for exhaustive key search

Key Size (bits)	Number of Alternative Keys	Time required at $10^6$ Decryption/ $\mu$ s
32	$2^{32} = 4.3 \times 10^9$	2.15 milliseconds
56	$2^{56} = 7.2 \times 10^{16}$	10 hours
128	$2^{128} = 3.4 \times 10^{38}$	$5.4 \times 10^{18}$ years
168	$2^{168} = 3.7 \times 10^{50}$	$5.9 \times 10^{30}$ years



# Key Points

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- Two main types of cryptosystems: classical and public key
- Classical cryptosystems encipher and decipher using the same key
  - Or one key is easily derived from the other
- Public key cryptosystems encipher and decipher using different keys
  - Computationally infeasible to derive one from the other