CSE 410/565: Computer Security

Instructor: Dr. Ziming Zhao

Cryptography

What is Cryptography

- Greek: “krypto” = hide
- Cryptography – secret writing. Originally, it is the study of encryption principles and methods
  - The most basic problem of cryptography is to ensure security of communication over insecure media
- Cryptographer

What is Cryptography

- Cryptanalysis – analyzing and breaking secrets. Originally, the study of principles and methods of deciphering ciphertext without knowing key

- Cryptanalyst

Cryptography

Can help

- Confidentiality
  - Obscure a message from eavesdroppers
- Integrity
  - Assure recipient that the message was not altered
- Authenticity
  - Verify the identity of the source of a message
- Non-repudiation
  - Convince a 3rd party that what was said is accurate

Cryptography & Security

- Most people argue cryptology is a branch of mathematics
- Security is about math, engineering, hardware, software, people, etc.
- Attackers try find the weakest link. In most cases, this is not the mathematics.
- Example: HeartBleed

Cryptography & Security

- Cryptographic tools are essential in designing secure solutions and their understanding is crucial to correct usage
- We'll look at these types of cryptographic tools
  - symmetric encryption
  - hash functions and message authentication codes
  - public-key encryption
  - digital signatures and certificates
  - pseudo-random number generators

Terminology

- Plaintext: the message to be transmitted or stored.
- Ciphertext: the disguised message.

- Key: Sequence that controls the operation and behavior of the cryptographic algorithm
- Keyspace: Total number of possible values of keys in a crypto algorithm

Terminology

- Encryption: the process of disguising a message so as to hide the information it contains; this process can include both encoding and enciphering.
- Protocol: an algorithm, defined by a sequence of steps, precisely specifying the actions of multiple parties in order to achieve an objective.
- Cryptosystem: The combination of algorithm, key, and key management functions used to perform cryptographic operations

Kerckhoff’s Principle

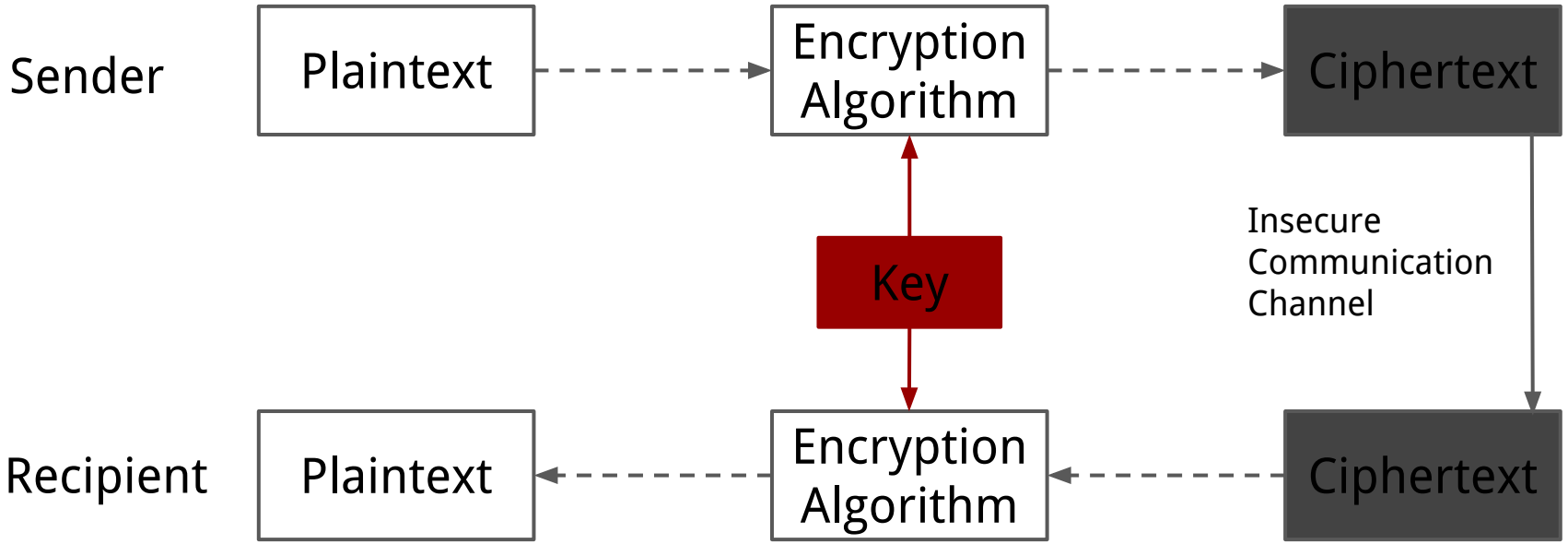
- French handbook of military cryptography, 1883
- A cryptosystem should be secure even if everything about the system, except the key, is public knowledge.
- Don’t assume enemy won’t know algorithm
  - Can capture machines, find patents, etc.
  - Too expensive to invent new algorithm if it might have been compromised

Symmetric Encryption I

Symmetric Encryption

- Symmetric (or secret-key) encryption means that the same key is used both for encryption and decryption
- The key must remain secret at both ends
- Such algorithms are:
  - normally very fast
  - can be used as primitives in more complex cryptographic protocols
  - the key often has a short lifetime

Symmetric Encryption



Ciphertext = E(K, Plaintext)
Plaintext = D(K, Ciphertext)

Symmetric Encryption

Ciphertext = E(K, Plaintext)
Plaintext = D(K, Ciphertext)

Desired properties:

1. Kerckhoff's: secrecy depends only on *K*
2. Without knowing *K* must be "hard" to invert
3. Easy to compute *E* and *D*

All cryptosystems until 1970s were like this. Asymmetric cryptosystems allow encryption and decryption keys to be different.

Symmetric Encryption Formally

More formally, a computationally secure symmetric key encryption scheme is defined as:

- a private-key encryption scheme consists of polynomial-time algorithms (*Gen*, *Enc*, *Dec*) such that
  - 1. Gen: on input the security parameter n, outputs key k
  - 2. Enc: on input a key k and a message $m \in \{0, 1\}^*$, outputs ciphertext c
  - 3. Dec: on input a key k and ciphertext c, outputs plaintext m
- we write $k \leftarrow Gen(1^n)$, $c \leftarrow Enc_k(m)$, and $m := Dec_k(c)$

Classic Symmetric Encryption Algorithms

Caesar Cipher

- Caesar used to *encrypt* his messages to communicate with his generals
- He would take each letter of the alphabet and replace it with a letter a certain distance away from that letter. When he got to the end, he would wrap back around to the beginning.
- Example with a shift of 3

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

Caesar Cipher

- Shift table

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

- Key: 3

- Plaintext: ATTACK
- Ciphertext: DWWDFN

- Keyspace: 25

Caesar Cipher

- Linux tr command

tr A-Za-z D-ZA-Cd-za-c

How to Attack Caesar Cipher?

- Attackers
  - Don't know the key or the shift table
  - Only knows Ciphertext

- Make a list of all possible keys and corresponding plaintext. If you expected the unencrypted text to be in English, you could easily figure out which word was right

- Small key space (25)

Extend Caesar to Simple Substitution Cipher

- Substitute each letter based on mapping
- Key is alphabet mapping:
  a -> J, b -> L, c -> B, d -> R, ..., z -> F

Substitution Cipher

- Number of possible keys
  26 (ways to choose what a maps to)
  * 25 (b can map to anything else)
  * 24 (c can map to anything else)
  … * 1 (only one choice left for z)
  = 26! = 403291461126605635584000000

  If every person on earth tried one per second, it would take 5B years to try them all.

  How secure is this cipher?

How to Attack Simple Substitution Cipher?

VKY PVDVY THSZYAPSVR NO HYI RNAB DV QTOODCN, UNGGNHCR UDCCYX VKY THSZYAPSVR DV QTOODCN DHX PNGYVSGYP UDCCYX PTHR QTOODCN, SP D LTQCSU AYPYDAUK THSZYAPSVR ISVK UDGLTPYP SH QTOODCN DHX DGKYAPV, HYI RNAB. VKY THSZYAPSVR IDP ONTHXYX DP D LASZDVY GYXSUDC UNCCYMY DHX CDVYA GYAMYX ISVK VKY PVDVY THSZYAPSVR NO HYI RNAB PRPVYG. SV SP NHY NO VKY VIN OCDMPKSL SHPVSVTVSNHP NO VKY PTHR PRPVYG. VKY THSZYAPSVR SP VKY CDAMYPV DHX GNPV UNGLAYKYHPSZY LTQCSU THSZYAPSVR SH VKY PVDVY NO HYI RNAB.

Letter Frequency Analysis

VKY PVDVY THSZYAPSVR NO HYI RNAB DV QTOODCN, UNGGNHCR UDCCYX VKY THSZYAPSVR DV QTOODCN DHX PNGYVSGYP UDCCYX PTHR QTOODCN, SP D LTQCSU AYPYDAUK THSZYAPSVR ISVK UDGLTPYP SH QTOODCN DHX DGKYAPV, HYI RNAB. VKY THSZYAPSVR IDP ONTHXYX DP D LASZDVY GYXSUDC UNCCYMY DHX CDVYA GYAMYX ISVK VKY PVDVY THSZYAPSVR NO HYI RNAB PRPVYG. SV SP NHY NO VKY VIN OCDMPKSL SHPVSVTVSNHP NO VKY PTHR PRPVYG. VKY THSZYAPSVR SP VKY CDAMYPV DHX GNPV UNGLAYKYHPSZY LTQCSU THSZYAPSVR SH VKY PVDVY NO HYI RNAB.

e 0.12702	s 0.06327	u 0.02758	p 0.01929	q 0.00095
t 0.09056	h 0.06094	m 0.02406	b 0.01492	z 0.00074
a 0.08167	r 0.05987	w 0.02360	v 0.00978	
o 0.07507	d 0.04253	f 0.02228	k 0.00772	
i 0.06966	l 0.04025	g 0.02015	j 0.00153	
n 0.06749	c 0.02782	y 0.01974	x 0.00150	

Word Frequency Analysis

VKY PVDVY THSZYAPSVR NO HYI RNAB DV QTOODCN, UNGGNHCR UDCCYX VKY THSZYAPSVR DV QTOODCN DHX PNGYVSGYP UDCCYX PTHR QTOODCN, SP D LTQCSU AYPYDAUK THSZYAPSVR ISVK UDGLTPYP SH QTOODCN DHX DGKYAPV, HYI RNAB. VKY THSZYAPSVR IDP ONTHXYX DP D LASZDVY GYXSUDC UNCCYMY DHX CDVYA GYAMYX ISVK VKY PVDVY THSZYAPSVR NO HYI RNAB PRPVYG. SV SP NHY NO VKY VIN OCDMPKSL SHPVSVTVSNHP NO VKY PTHR PRPVYG. VKY THSZYAPSVR SP VKY CDAMYPV DHX GNPV UNGLAYKYHPSZY LTQCSU THSZYAPSVR SH VKY PVDVY NO HYI RNAB.

Most common trigrams in English:
the = 6.4%
and = 3.4%

Word Frequency Analysis

THE PTDTE THSZEAPSTR NO HEI RNAB DT QTOODCN, UNGGNHCR UDCCEX THE THSZEAPSTR DT QTOODCN DHX PNGETSGEP UDCCEX PTHR QTOODCN, SP D LTQCSU AEPEDAUH THSZEAPSTR ISTH UDGLTPEP SH QTOODCN DHX DGHEAPT, HEI RNAB. THE THSZEAPSTR IDP ONTHXEX DP D LASZDTE GEXSUDC UNCCEME DHX CDTEA GEAMEX ISTH THE PTDTE THSZEAPSTR NO HEI RNAB PRPTEG. ST SP NHE NO THE TIN OCDMPHSL SHPTSTTTSNHP NO THE PTHR PRPTEG. THE THSZEAPSTR SP THE CDAMEPT DHX GNPT UNGLAEHEHPSZE LTQCSU THSZEAPSTR SH THE PTDTE NO HEI RNAB.

tr VKY THE

Guess?

THE PTDTE THSZEAPSTR NO HEI RNAB DT QTOODCN, UNGGNHCR UDCCEX THE THSZEAPSTR DT QTOODCN DHX PNGETSGEP UDCCEX PTHR QTOODCN, SP D LTQCSU AEPEDAUH THSZEAPSTR ISTH UDGLTPEP SH QTOODCN DHX DGHEAPT, HEI RNAB. THE THSZEAPSTR IDP ONTHXEX DP D LASZDTE GEXSUDC UNCCEME DHX CDTEA GEAMEX ISTH THE PTDTE THSZEAPSTR NO HEI RNAB PRPTEG. ST SP NHE NO THE TIN OCDMPHSL SHPTSTTTSNHP NO THE PTHR PRPTEG. THE THSZEAPSTR SP THE CDAMEPT DHX GNPT UNGLAEHEHPSZE LTQCSU THSZEAPSTR SH THE PTDTE NO HEI RNAB.

Guess?

THE PTATE THSZEAPSTR NO HEI RNAB AT QTOOACN, UNGGNHCR UACCEX THE THSZEAPSTR AT QTOOACN AHX PNGETSGEP UACCEX PTHR QTOOACN, SP A LTQCSU AEPEAAUH THSZEAPSTR ISTH UAGLTPEP SH QTOOACN AHX AGHEAPT, HEI RNAB. THE THSZEAPSTR IAP ONTHXEX AP A LASZATE GEXSUAC UNCCEME AHX CATEA GEAMEX ISTH THE PTATE THSZEAPSTR NO HEI RNAB PRPTEG. ST SP NHE NO THE TIN OCAMPHSL SHPTSTTTSNHP NO THE PTHR PRPTEG. THE THSZEAPSTR SP THE CAAMEPT AHX GNPT UNGLAEHEHPSZE LTQCSU THSZEAPSTR SH THE PTATE NO HEI RNAB.

tr VKYD THEA

Guess?

THE PTATE THSZEAPSTR NO HEI RNAB AT QTOOACN, UNGGNHCR UACCEX THE THSZEAPSTR AT QTOOACN AHX PNGETSGEP UACCEX PTHR QTOOACN, SP A LTQCSU AEPEAAUH THSZEAPSTR ISTH UAGLTPEP SH QTOOACN AHX AGHEAPT, HEI RNAB. THE THSZEAPSTR IAP ONTHXEX AP A LASZATE GEXSUAC UNCCEME AHX CATEA GEAMEX ISTH THE PTATE THSZEAPSTR NO HEI RNAB PRPTEG. ST SP NHE NO THE TIN OCAMPHSL SHPTSTTTSNHP NO THE PTHR PRPTEG. THE THSZEAPSTR SP THE CAAMEPT AHX GNPT UNGLAEHEHPSZE LTQCSU THSZEAPSTR SH THE PTATE NO HEI RNAB.

tr VKYD THEA

Guess?

THE STATE THSZEASSTR NO HEI RNAB AT QTOOACN, UNGGNHCR UACCEX THE THSZEASSTR AT QTOOACN AHX SNGETSGES UACCEX STHR QTOOACN, SS A LTQCSU AESEAAUH THSZEASSTR ISTH UAGLTSES SH QTOOACN AHX AGHEAST, HEI RNAB. THE THSZEASSTR IAS ONTHXEX AS A LASZATE GEXSUAC UNCCEME AHX CATEA GEAMEX ISTH THE STATE THSZEASSTR NO HEI RNAB SRSTEG. ST SS NHE NO THE TIN OCAMSHSL SHSTSTTTSNHS NO THE STHR SRSTEG. THE THSZEASSTR SS THE CAAMEST AHX GNST UNGLAEHEHSSZE LTQCSU THSZEASSTR SH THE STATE NO HEI RNAB.

tr VKYDP THEAS

Pattern Analysis and Guess

THE STATE UNIVERSITY OF NEW YORK AT BUFFALO, COMMONLY CALLED THE UNIVERSITY AT BUFFALO AND SOMETIMES CALLED SUNY BUFFALO, IS A PUBLIC RESEARCH UNIVERSITY WITH CAMPUSES IN BUFFALO AND AMHERST, NEW YORK. THE UNIVERSITY WAS FOUNDED AS A PRIVATE MEDICAL COLLEGE AND LATER MERGED WITH THE STATE UNIVERSITY OF NEW YORK SYSTEM. IT IS ONE OF THE TWO FLAGSHIP INSTITUTIONS OF THE SUNY SYSTEM. THE UNIVERSITY IS THE LARGEST AND MOST COMPREHENSIVE PUBLIC UNIVERSITY IN THE STATE OF NEW YORK.

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tr A-Z DQUXYOMKSFBCGHNLEAPVTZIJRW
tr DQUXYOMKSFBCGHNLEAPVTZIJRW A-Z
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Simple Substitution Doesn’t Work

- A large space of keys is not enough
- Monoalphabetic
  - The same plaintext letters are always replaced by the same ciphertext letters
- Doesn’t hide statistical properties of plaintext. Doesn’t hide relationships in plaintext
- Natural languages are very redundant

Make it Harder?

- Hide statistical properties
  - Encrypt “e” with 12 different symbols, “t” with 9 different symbols, etc.
- Polyalphbetic cipher
  - Use different substitutions
- Transposition (permutation)
  - Scramble order of units; reorder units of plaintext

Transposition Cipher

A Transposition Cipher is a cipher in which the plaintext message is rearranged by some means.

These hide the message by rearranging the letter order, without altering the actual letters used.

Also called permutation ciphers.

Transposition Cipher

T O D A Y
+ I S + M
O N D A Y

Write across rows. Read in a counter clockwise spiral from top-left.

Encrypt(TODAY+IS+MONDAY) = T+ONDAYMYADOIS+

Perfectly Secure Cipher: One-Time Pad

- Random key that is as long as the message, so that the key need not be repeated.
- The key is to be used to encrypt and decrypt a single message, and then is discarded.
- Each new message requires a new key of the same length as the new message.

Perfectly Secure Cipher: One-Time Pad

- In 1919, Gilbert Verman got a patent that states a cipher in which each character in a message was electrically combined with a character on a paper tape key

UNITED STATES PATENT OFFICE.

GILBERT S. VERNAM, OF BROOKLYN, NEW YORK, ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK.

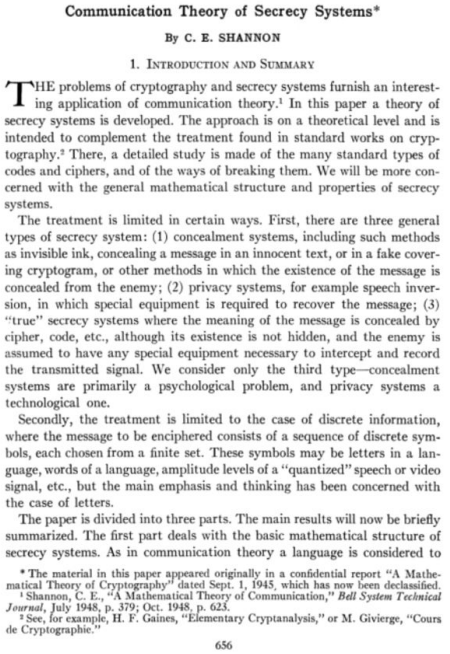
SECRET SIGNALING SYSTEM.

1,310,719. Specification of Letters Patent. Patented July 22, 1919.

Application filed September 13, 1918. Serial No. 253,962.

Perfectly Secure Cipher: One-Time Pad

- Later, U.S. Army captain Joseph Mauborgne recognized that if the character sequence on the key tape could be completely random, cryptanalysis would be more difficult
- Proved perfectly secure by Claude Shannon in “Communication Theory of Secrecy Systems”,1949



Communication Theory of Secrecy Systems*

By C. E. SHANNON

1. Introduction and Summary

THE problems of cryptography and secrecy systems furnish an interesting application of communication theory.[1] In this paper a theory of secrecy systems is developed. The approach is on a theoretical level and is intended to complement the treatment found in standard works on cryptography.[2] There, a detailed study is made of the many standard types of codes and ciphers, and of the ways of breaking them. We will be more concerned with the general mathematical structure and properties of secrecy systems.

The treatment is limited in certain ways. First, there are three general types of secrecy system: (1) concealment systems, including such methods as invisible ink, concealing a message in an innocent text, or in a fake covering cryptogram, or other methods in which the existence of the message is concealed from the enemy; (2) privacy systems, for example speech inversion, in which special equipment is required to recover the message; (3) "true" secrecy systems where the meaning of the message is concealed by cipher, code, etc., although its existence is not hidden, and the enemy is assumed to have any special equipment necessary to intercept and record the transmitted signal. We consider only the third type—concealment systems are primarily a psychological problem, and privacy systems a technological one.

Secondly, the treatment is limited to the case of discrete information, where the message to be enciphered consists of a sequence of discrete symbols, each chosen from a finite set. These symbols may be letters in a language, words of a language, amplitude levels of a "quantized" speech or video signal, etc., but the main emphasis and thinking has been concerned with the case of letters.

The paper is divided into three parts. The main results will now be briefly summarized. The first part deals with the basic mathematical structure of secrecy systems. As in communication theory a language is considered to

* The material in this paper appeared originally in a confidential report "A Mathematical Theory of Cryptography" dated Sept. 1, 1945, which has now been declassified.
[1] Shannon, C. E., "A Mathematical Theory of Communication," *Bell System Technical Journal*, July 1948, p. 379; Oct. 1948, p. 623.
[2] See, for example, H. F. Gaines, "Elementary Cryptanalysis," or M. Givierge, "Cours de Cryptographie."

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Perfectly Secure Cipher: One-Time Pad

- It produces random output that bears no statistical relationship to the plaintext
- Because the ciphertext contains no information whatsoever about the plaintext (except the length), there is simply no way to break the code
- For any given ciphertext, all plaintexts are equally possible

Is it practical?

- Need to generate truly random pad values as long as all messages
- Generating truly random keys/numbers/values is hard
- Need to securely distribute the one-time pad values

Modern Symmetric Encryption Algorithms

From Classic to Modern Ciphers

Consider using several ciphers in succession to make harder

- Two substitutions make a more complex substitution
- Two transpositions make more complex transposition
- But a substitution followed by a transposition makes a new much harder cipher

Principle of Modern Ciphers

- Use both substitution and transposition
- Proved by C. E. Shannon
  - Using information theory in 1945
  - Product ciphers
    - combines two or more transformations in a manner intending that the resulting cipher is more secure.
- Formulate the principles of “confusion” (standing for substitution) and “diffusion” (standing for transposition)

Confusion and Diffusion

Modern substitution ciphers take in N bits and substitute N bits with M bits using lookup table: called ***S-Boxes***

Modern transposition ciphers take in N bits and permute using lookup table: called ***P-Boxes***

Symmetric Encryption

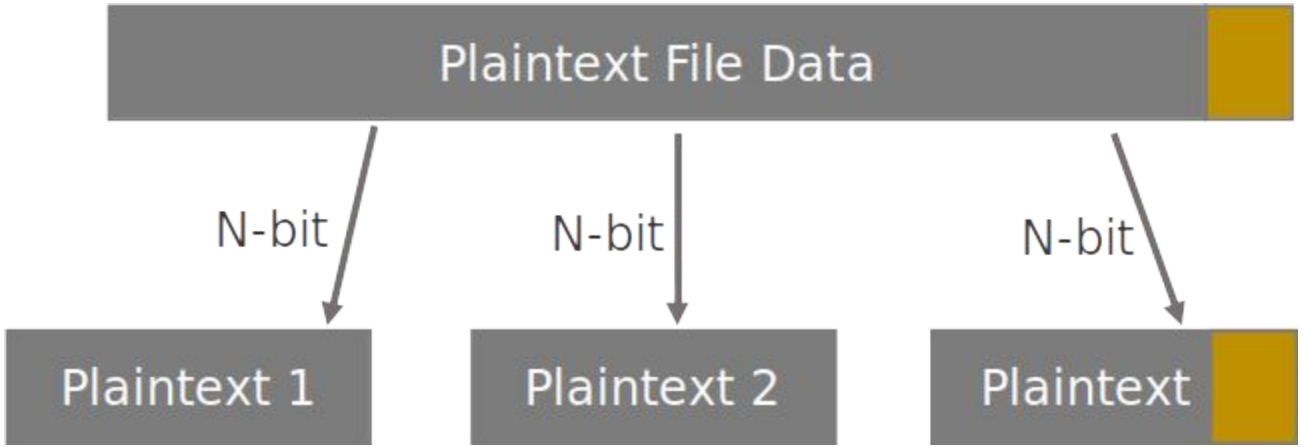
- There are two types of symmetric key algorithms:
  - block ciphers
    - the key has a fixed size
    - prior to encryption, the message is partitioned into blocks
    - each block is encrypted and decrypted separately
  - stream ciphers
    - the message is processed as a stream
    - pseudo-random generator is used to produce a long key stream from a short key

Block Ciphers

- The algorithm maps an ***n-bit plaintext block*** to an ***n-bit ciphertext block***
- Most modern block ciphers are ***product ciphers***
  - we sequentially apply more than one operation to the message
- Often a sequence of permutations and substitutions is used
- A common design for an algorithm is to proceed in iterations
  - one iteration is called a ***round***
  - each round consists of similar operations
  - ***ith*** round key ***ki*** is derived from the secret key ***k*** using a fixed, public algorithm

Block Ciphers

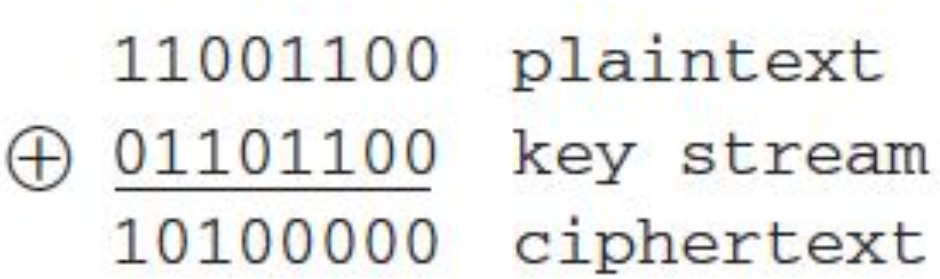
- Divide input bit stream into n-bit sections



- In a good block cipher, each output bit is a function of all n input bits and all k key bits

Stream Ciphers

- Process message bit by bit (as a stream)
- Have a pseudo random keystream combined (XOR) with plaintext bit by bit
- Randomness of stream key completely destroys statistically properties in message



Attacks Against Symmetric Encryption

- Encryption and decryption algorithms are assumed to be known to the adversary
- Types of attacks
  - ciphertext only attack: adversary knows a number of ciphertexts
  - known plaintext attack: adversary knows some pairs of ciphertexts and corresponding plaintexts
  - chosen plaintext attack: adversary knows ciphertexts for messages of its choice
  - chosen ciphertext attack: adversary knows plaintexts for ciphertexts of its choice
- We want a general-purpose algorithm to sustain all types of attacks

Security Against Chosen-Plaintext Attacks

- In chosen-plaintext attack (CPA), adversary A is allowed to ask for encryptions of messages of its choice – it is active and adaptive
- A is given black-box access to encryption oracle and can query it on different messages
- A is asked to distinguish between encryptions of messages of its choice