Basics of Data Encryption
CS 239
Security for System Software
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Outline

- What is data encryption?
- Basic encryption mechanisms
- Stream and block ciphers
- Characteristics of good ciphers

Data Encryption Concepts

- Introduction
- Terminology
- Basics of encryption algorithms
- Cryptanalysis

Introduction to Encryption

- Much of computer security is about keeping secrets
- One powerful method of making data secret is to make it hard for others to read
- While (usually) making it simple for authorized parties to read

Encryption

- Encryption is the process of hiding information in plain sight
- Transform the secret data into something else
- Even if the attacker can see the transformed data, he can't understand the underlying secret

Encryption and Data Transformations

- Encryption is all about transforming the data
- A given bit or byte pattern is transformed to some other bit or byte pattern
- Usually in a reversible way

Encryption Terminology

- Encryption is typically described in terms of sending a message
  - Though it's used for many other purposes
- The sender is *S*
- The receiver is *R*
- The transmission medium is *T*
- And the attacker is *O*

More Terminology

- *Encryption* is the process of making message unreadable/unalterable by *O*
- *Decryption* is the process of making the encrypted message readable by *R*
- A system performing these transformations is a *cryptosystem*
  - Rules for transformation sometimes called a *cipher*

Plaintext and Ciphertext

- *Plaintext* is the original form of the message (often referred to as *P*)

```
Transfer
$100 to my
savings
account
```

- *Ciphertext* is the encrypted form of the message (often referred to as *C*)

```
Sqzmredq
#099 sn lx
rzuhmfr
zbbntms
```


Very Basics of Encryption Algorithms

- Most use a *key* to perform encryption and decryption
  - Referred to as *K*
- The key is a secret
- Without the key, decryption is hard
- With the key, decryption is easy

Terminology for Encryption Algorithms

- The encryption algorithm is referred to as $E()$
- $C = E(K,P)$
- The decryption algorithm is referred to as $D()$
- The decryption algorithm also has a key

Symmetric and Asymmetric Encryption Systems

- In a symmetric encryption system, the keys for E and D are the same

  $P = D(K, C)$

  Expanding, $P = D(K, E(K,P))$
- In an asymmetric system, different keys are used for encryption and decryption

  $C = E(K_E,P)$

  $P = D(K_D,C)$

Characteristics of Keyed Encryption Systems

- If you change the key (without changing anything else in the encryption system), a given plaintext is encrypted to a different ciphertext
- Same applies to decryption
- Decryption should be hard without knowing the key

Cryptanalysis

- The process of trying to break a cryptosystem
- Finding the meaning of an encrypted message without being given the key

Forms of Cryptanalysis

- Analyze an encrypted message and deduce its contents
- Analyze one or more encrypted messages to find a common key
- Analyze a cryptosystem to find a fundamental flaw

Breaking Cryptosystems

- Most cryptosystems are breakable
- Some just cost more to break than others
- The job of the cryptosystem is to make the cost infeasible
  - Or incommensurate with the benefit extracted

Types of Attacks on Cryptosystems

- Ciphertext only
- Known plaintext
- Chosen plaintext
- Algorithm and ciphertext

Ciphertext Only

- No a priore knowledge of plaintext
- Or details of algorithm
- Must work with probability distributions, patterns of common characters, etc.
- Hardest type of attack

Known Plaintext

- Full or partial
- Cryptanalyst has matching sample of ciphertext and plaintext
- Or may know something about what ciphertext represents
  - E.g., an IP packet with its headers

Chosen Plaintext

- Cryptanalyst can submit chosen samples of plaintext to the cryptosystem
- And recover the resulting ciphertext
- Clever choices of plaintext may reveal many details

Algorithm and Ciphertext

- Cryptanalyst knows the algorithm and has a sample of ciphertext
- But not the key, and may not get any more similar ciphertext
- Can use "exhaustive" runs of algorithm against guesses at plaintext
- Password guessers often work this way

Basic Encryption Methods

- Substitutions
  - Monoalphabetic
  - Polyalphabetic
- Permutations

Substitution Ciphers

- Substitute one or more characters in a message with one or more different characters
- Using some set of rules
- Decryption is performed by reversing the substitutions

Example of a Simple Substitution Cipher

How did this transformation happen?

```
Sqzmredq
#099 sn lx
rzuhmfr
zbbntms
```

⇒

```
Sqzmredq
#099 sn lx
rzuhmfr
zbbntms
```

Every letter was changed to the "next lower" letter

Caesar Ciphers

- A simple substitution cipher like the previous example
  - Supposedly invented by Julius Caesar
- Translate each letter a fixed number of positions in the alphabet
- Reverse by translating in opposite direction

Is the Caesar Cipher a Good Cipher?

- Not really
- It’s simple, but
- It’s simple
- Fails to conceal many important characteristics of the message
- Which makes cryptanalysis easier
- Limited number of useful keys

How Would Cryptanalysis Attack a Caesar Cipher?

- Letter frequencies
- In English (and other alphabetic languages), some letters occur more frequently than others
- Caesar ciphers translate all occurrences of a given letter into the same cipher letter
- All you need is the offset

More On Frequency Distributions

- In most languages, some letters used more than others
  - In English, “e,” “t,” and “s” common
- True even in non-natural languages
  - Certain characters appear frequently in C code
  - Zero appears often in much numeric data

Cryptanalysis and Frequency Distribution

- If you know what kind of data was encrypted, you can (usually) use frequency distributions to break it
- Especially for monoalphabetic substitutions

Breaking Monoalphabetic Ciphers

- Identify (or guess) kind of data
- Count frequency of each encrypted symbol
- Match to observed frequencies of other symbols in other kinds of data
- Provides probable mapping of cipher
- The more ciphertext available, the more reliable this technique

Example

- With ciphertext “Sqzmredq #099 sn lx rzuhmfr zbbntms”
- Frequencies -

a	0	b	2	c	0	d	1	e	1
f	1	g	0	h	1	i	0	j	0
k	0	l	1	m	3	n	2	o	0
p	0	q	2	r	3	s	3	t	1
u	1	v	0	w	0	x	1	y	0
z	3								

Applying Frequencies To Our Example

- The most common English letters are typically “e,” “t,” “a,” “o,” and “s”
- We would guess that some of the cipher symbols “m,” “r,” “s,” “z,” “b,” “n,” and “q” map to those
- Four out of five of the common English letters in the plaintext are in the set

More Complex Substitutions

- Monoalphabetic substitutions - Each plaintext letter maps to a single, unique ciphertext letter
- Any mapping is permitted
- Key can provide method of determining the mapping
  - Key could <u>be</u> the mapping

Are These Monoalphabetic Ciphers Better?

- Only a little
- Finding the mapping for one character doesn’t give you all mappings
- But the same simple techniques can be used to find the other mappings
- Generally insufficient for anything serious

Codes and Monoalphabetic Ciphers

- Codes are sometimes considered different than ciphers
- A series of important words or phrases are replaced with meaningless words or phrases
- E.g., “Transfer $100 to my savings account” becomes
  - “The hawk flies at midnight”

Are Codes More Secure?

- Depends
- Frequency attacks based on letters don’t work any more
- But frequency attacks based on phrases may
- And other tricks may cause problems

Polyalphabetic Ciphers

- Ciphers that don't always translate a given plaintext character into the same ciphertext character
- For example, use different substitutions for odd and even positions

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Example of Simple Polyalphabetic Cipher

- Move one character "up" in even positions, one character "down" in odd positions
- Note that same character translates to different characters in some cases

```
Transfer
$100 to my
savings
account
```

```
Sszorgds
%019 sp nx
tbujmhr
zdbptos
```

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Are Polyalphabetic Ciphers Better?

- Depends
- On how easy it is to determine the pattern of substitutions
- If it's easy, then you've gained little

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Cryptanalysis of Our Example

- Consider all even characters as one set
- And all odd characters as another set
- Now apply basic cryptanalysis to each set
- The transformations fall out pretty easily

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How About For More Complex Patterns?

- Good if the attacker doesn't know the choices of which characters get transformed which way
- Patterns should attempt to be well hidden
- But known methods still exist for breaking them

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Methods of Attacking Polyalphabetic Ciphers

- Kasiski method tries to find where repetitions of the encryption pattern occur
- Index of coincidence predicts the number of alphabets used to perform the encryption
- Both require lots of ciphertext

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However, . . .

- There is a "perfect" substitution cipher
- One that is theoretically (and practically) unbreakable without the key
- One-time pads!

One-Time Pads

- Essentially, use a new substitution alphabet for <u>every</u> character
- Substitution alphabets chosen purely at random
  - These constitute the key
- Provably unbreakable without knowing this key

Example of One Time Pads

- Usually explained with bits, not characters
- We shall use a highly complex cryptographic transformation:
  - XOR
- And a three bit message
  - 010

One Time Pads at Work

0	1	0

Flip some coins to get random numbers

0	1	1

Apply our sophisticated cryptographic algorithm

What's so secure about that?

<u>Any</u> key was equally likely

<u>Any</u> plaintext could have produced this message with one of those keys

Security of One-Time Pads

- If the key is truly random, provable that it can't be broken without the key
- But there are problems
- Need one bit of key per bit of message
- Key distribution is painful
- Synchronization of keys is vital
- A good random number generator is hard to find

Attacking One-Time Pads

- Not much fun
  - But then, neither is using them
- Essentially, you attack their random number generator
- Hope that it isn't really random, and try to find its non-random characteristics

One-Time Pads and Cryptographic Snake Oil

- You regularly hear companies claim they have “unbreakable” cryptography
- Usually based on one-time pads
- But typically misused
  - Pads distributed with some other crypto mechanism
  - Pads generated with non-random process
  - Pads reused

Permutation Ciphers

- Instead of substituting different characters, scramble up the existing characters
- Use algorithm based on the key to control how they’re scrambled
- Decryption uses key to unscramble

Characteristics of Permutation Ciphers

- Doesn’t change the characters in the message
  - Just where they occur
- Thus, character frequency analysis doesn’t help cryptanalyst

Columnar Transpositions

- Write the message characters in a series of columns
- Copy from top to bottom of first column, then second, etc.

Example of Columnar Transposition

T	r	a	n	s	f
e	r		$	1	0
0		t	o		m
y		s	a	v	i
n	g	s		a	c
c	o	u	n	t	

Becomes

“Te0yncrr goa tssun$oa ns1 vatf0mic ”

Example of Columnar Substitution

How did this transformation happen?

T	r	a	n	s	f
e	r		$	1	0
0		t	o		m
y		s	a	v	i
n	g	s		a	c
c	o	u	n	t	

⇨

T	e	0	y	n	c
r	r			g	o
a		t	s	s	u
n	$	o	a		n
s	1		v	a	t
f	0	m	i	c	

Attacking Columnar Transformations

- The trick is figuring out how many columns were used
- Use information about digrams, trigrams, and other patterns
- Digrams are letters that frequently occur together (re, th, en, for example)
- For each possibility, check digram frequency

For Example,

- In our case, the presence of numerals in the text is suspicious
  - One might guess the numerals belong together
  - And maybe the dollar sign with them
- Most of this analysis is more complicated

Double Transpositions

- Do it twice
- Using different numbers of columns each time
- Find pairs of letters that probably appeared together in the plaintext
- Figure out what transformations would put them in their positions in the ciphertext

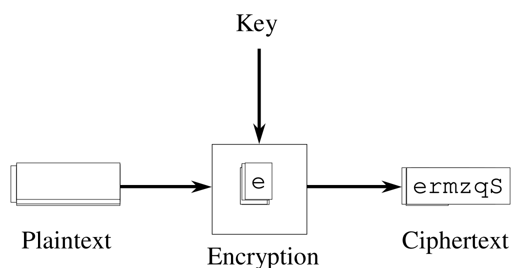
Generalized Transpositions

- Any algorithm can be used to scramble the text
- Usually somehow controlled by a key
- Generality of possible transpositions makes cryptanalysis harder

Stream and Block Ciphers

- Stream ciphers convert one symbol of plaintext immediately into one symbol of ciphertext
- Block ciphers work on a given sized chunk of data at a time

Stream Ciphers



Advantages of Stream Ciphers

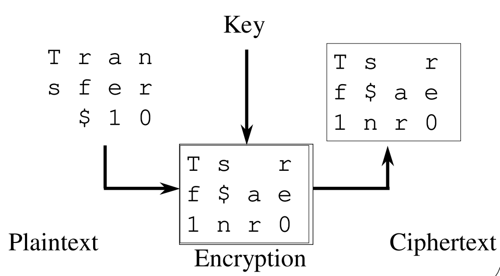
+ Speed of encryption and decryption
  - Each symbol encrypted as soon as it's available
+ Low error propagation
  - Errors affect only the symbol where the error occurred

Disadvantages of Stream Ciphers

– Low diffusion
  - Each symbol separately encrypted
  - Each ciphertext symbol only contains information about one plaintext symbol

– Susceptible to insertions and modifications

Block Ciphers



Advantages of Block Ciphers

+ Diffusion
  - Easier to make a set of encrypted characters depend on each other
+ Immunity to insertions
  - Encrypted text arrives in known lengths

Disadvantages of Block Ciphers

– Slower
  - Need to wait for block of data before encryption/decryption starts

– Worse error propagation
  - Errors affect entire blocks

Characteristics of Good Ciphers

- Well matched to requirements of application
  – Amount of secrecy required should match labor to achieve it
- Freedom from complexity
  – The more complex algorithms or key choices are, the worse

More Characteristics

- Simplicity of implementation
  - Seemingly more important for hand ciphering
  - But relates to probability of errors in computer implementations
- Errors should not propagate

Yet More Characteristics

- Ciphertext size should be same as plaintext size
- Encryption should maximize *confusion*
  - Relation between plaintext and ciphertext should be complex
- Encryption should maximize *diffusion*
  - Plaintext information should be distributed throughout ciphertext