Overview

- What is cryptography?
- Classic cryptosystems
  - The Caesar cipher
  - Monoalphabetic replacement cipher
  - The one-time pad
- Types of cryptosystems
  - Codes vs. ciphers
  - Symetric-key vs. assymetric-key
  - Hybrid cryptosystems

What is Cryptography?

- Text defines **Cryptography** as the science of designing and analyzing cryptosystems which are used to disguise messages so that only certain people can see through the disguise
- A classic cryptosystem: the Caesar cipher
  - Replace every ‘A’ in the message with a ‘D’
  - Replace every ‘B’ in the message with a ‘E’
  - Replace every ‘C’ in the message with a ‘F’
  - Etc.

The Caesar Cipher

- Camouflage the message “ATTACK AT DAWN” by writing “DWWDFN DW GDZQ”

- “ATTACK AT DAWN” is **plaintext**
- “DWWDFN DW GDZQ” is **ciphertext**

- **Encryption** is the process used to convert plaintext into ciphertext
- **Decryption** is the process used to convert ciphertext into plaintext

The Key to a Cryptosystem

- Assumptions:
  - Encryption and decryption algorithms are public
  - Their results depend on some value known as a **key**
  - Protection is based solely on the secrecy of the key
  - Encryption for the Caesar cipher = "shift forward by *n*"
  - Decryption for the Caesar cipher = "shift backwards by *n*"
  - The key for the Caesar cipher is *n*
    - Encryption: $C_i = (P_i + n) \bmod 26$
    - Decryption: $P_i = (C_i - n) \bmod 26$

The Keyspace for a Cryptosystem

- For the Caesar cipher, any value from the set {1, 2, …, 25} can be a key
- The set of usable keys is referred to as a cryptosystem’s **keyspace**
- Cryptosystems with a small keyspace are vulnerable to a **brute-force search** for the proper key

What is Cryptanalysis?

- **Cryptanalysis** the science of attacking cryptosystems
  - Deduce the key and/or
  - recover plaintext
- Assume adversary knows the ciphertext and encryption algorithm

Cryptanalysis of the Caesar Cipher

- Ciphertext = “GRR MGAR OY JOBOJKJ OT ZNXKK VGXZY”
- Perform decryption with each possible key:
  - Plaintext (if key is 1): FQQ LFZQ NX INANIJI NS YMWJJ UFWYX
  - Plaintext (if key is 2): EPP KEYP MW HMZMHIH MR XLVII TEVXW
  - Plaintext (if key is 3): DOO JDXO LV GLYLGHG LQ WKUHH SDUWV
  - Plaintext (if key is 4): CNN ICWN KU FKXKFGF KP VJTGG RCTVU
  - Plaintext (if key is 5): BMM HBVM JT EJWJEFE JO UISFF QBSUT
  - Plaintext (if key is 6): ALL GAUL IS DIVIDED IN THREE PARTS
  - Plaintext (if key is 7): ZKK FZTK HR CHUHCDC HM SGQDD OZQSR

    . . .
  - Plaintext (if key is 26): GRR MGAR OY JOBOJKJ OT ZNXKK VGXZY
- Only one of the plaintexts above (the one corresponding to a key of 6) makes sense

The Monoalphabetic Replacement Cipher

- Similar to the Caesar cipher but with much larger keyspace
- A key is any permutation of the 26 letters of the alphabet
  - Example: JQPLMZKOWHANXIEURYTGSFDVCB
- Defines a **cipher alphabet**:

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
J	Q	P	L	M	Z	K	O	W	H	A	N	X	I	E	U	R	Y	T	G	S	F	D	V	C	B

The Monoalphabetic Replacement Cipher - Encryption

- Plaintext (*by Thomas Jefferson*):
  - "I prefer freedom with danger to slavery with ease."
- Cipher alphabet

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
J	Q	P	L	M	Z	K	O	W	H	A	N	X	I	E	U	R	Y	T	G	S	F	D	V	C	B

- Encryption: replace each plaintext letter with the corresponding cipher letter from the cipher alphabet
- Examples:
  - Replace every "A" in the plaintext with a "J"
  - Replace every "B" in the plaintext with a "Q"
  - Replace every "C" in the plaintext with a "P"
  - Etc.

The Monoalphabetic Replacement Cipher – Encryption (cont)

- Plaintext:
  - "I prefer freedom with danger to slavery with ease."
- Cipher alphabet:

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
J	Q	P	L	M	Z	K	O	W	H	A	N	X	I	E	U	R	Y	T	G	S	F	D	V	C	B

- Ciphertext:
  - "W uymzmy zymmlex dwgo ljikmy ge tnjfmyc dwgo mjtm."

The Monoalphabetic Replacement Cipher - Decryption

- Ciphertext:
  - "W uymzmy zymmlex dwgo ljikmy ge tnjfmyc dwgo mjtm."
- Cipher alphabet

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
J	Q	P	L	M	Z	K	O	W	H	A	N	X	I	E	U	R	Y	T	G	S	F	D	V	C	B

- Decryption: replace each plaintext letter with the corresponding cipher letter from the cipher alphabet
- Plaintext:
  - "I prefer freedom with danger to slavery with ease."

The Monoalphabetic Replacement Cipher - Keyspace

- Key = any permutation of the 26 letters of the alphabet
- Keyspace contains 26! elements
  - 403,291,461,126,605,635,584,000,000
- Exhaustive search at one trillion keys per second takes:
  - 400 trillion seconds
  - More than 12 million years
- It is fairly easy to perform cryptanalysis on this cipher, but not using exhaustive search

The Monoalphabetic Replacement Cipher – Weak Keys

- Some keys result in better-disguised ciphertext than others:
  - Using JQPLMZKOWHANXIEURYTGSFDVCB as a key gives:
    "W uymzmy zymmlex dwgo ljikmy ge tnjfmyc dwgo mjtm."
  - Using ABCDEFGHIJKLMNOPQRSTUVWXYZ as a key gives:
    "I prefer freedom with danger to slavery with ease."
  - Using ABCDEFGHIJKLMNOPQRSTUVWXZY as a key gives:
    "I prefer freedom with danger to slaverz with ease."
- Keys that produce weak ciphertext are called **weak** keys
- Weak keys need not be a problem so long as:
  - They are not used
  - The vast majority of the keys are not weak

One-Time Pads

- Unbreakable
- Sender and receiver must generate a large, non-repeating set of truly random key letters
  - E.g. IPKLPSFHGQYPWKQMSVCX…
- Sender uses each key letter on the pad to encrypt one letter of plaintext
  - $C_i = (P_i + K_i) \bmod 26$
- Receiver uses each key letter on the pad to decrypt one letter of ciphertext
  - $P_i = (C_i - K_i) \bmod 26$

One-Time Pad Encryption - Example

- One time pad:
  IPKLPSFHGQYPWKQMSVCX…
- Plaintext:
  "ATTACKATDAWN"
- Ciphertext:
  "JJEMSDGBKRVD"

A (1) + I (9) mod 26 = J (10)	A (1) + F (6) mod 26 = G (7)
T (20) + P (16) mod 26 = J (10)	T (20) + H (8) mod 26 = B (2)
T (20) + K (11) mod 26 = E (5)	D (4) + G (7) mod 26 = K (11)
A (1) + L (12) mod 26 = M (13)	A (1) + Q (17) mod 26 = R (18)
C (3) + P (16) mod 26 = S (19)	W (23) + Y (25) mod 26 = V (22)
K (11) + S (19) mod 26 = D (4)	N (14) + P (16) mod 26 = D (4)

One-Time Pad Decryption - Example

- One time pad:

  IPKLPSFHGQYPWKQMSVCX…
- Ciphertext:

  “JJEMSDGBKRVD”
- Plaintext:

  “ATTACKATDAWN”

  J (10) - I (9) mod 26 = A (1)

  J (10) - P (16) mod 26 = T (20)

  E (5) - K (11) mod 26 = T (20)

  .

  .

One-Time Pad - Security

- Why is it an unbreakable encryption algorithm?
  - Assume the adversary doesn't know any of the key letters on the one-time pad
  - If they were generated truly randomly then all key letters are equally likely in each position
  - So when the adversary sees the ciphertext, "JJEMSDGBKRVD"
  - <u>All plaintexts are equally possible</u>:

    JJEMSDGBKRVD = ATTACKATDAWN for IPKLPSFHGQYP

    JJEMSDGBKRVD = ELVISISALIVE for EXIDZUNAYIZY

    .

    .

One-Time Pad - Security (cont)

- Every plaintext message is equally possible
- No way for an adversary to determine which plaintext is correct
- A truly random key sequence added to a nonrandom plaintext produces a truly random ciphertext
- No algorithm will enable the adversary to choose the proper plaintext with better than random probability

One-Time Pads - Drawbacks

- Key must be as long as the message
- Security depends on adversary never obtaining a copy of the pad
  - Pad must be distributed securely to sender and receiver
  - Pad must be destroyed immediately after use to lessen the likelihood that old messages will be compromised
- Security depends on using the cryptosystem properly
  - Pad must be generated truly randomly (pseudo-random won't due)
  - No part of the pad can ever be reused

Types of Cryptosystems

- Codes, ciphers, or a combination of the two
- Ciphers (e.g. the Caesar cipher)
  - Transform each plaintext block into a ciphertext block
  - **Block** is a fixed-size unit on which a cryptosystem operates
    - Single character (e.g. Caesar cipher)
    - Two or more characters

Ciphers

- **Substitution** ciphers apply some function to the plaintext block and key to produce a block of ciphertext which replaces the plaintext (e.g. the Caesar cipher)
- **Transposition** ciphers shuffle the blocks into a new order that depends on the plaintext block and key

A	T	T	A	C
K		A	T	
D	A	W	N	

= “AKDT ATAWATNC”

A	K	D
T		A
T	A	W
A	T	N
C		

= “ATTACK AT DAWN”

Codes

- Sender and receiver each have a copy of a **codebook** which specifies one or more **codewords** for each word that might be used in a message:

Word	Codeword
AT	September
ATTACK	March
ATTACK	December
DAWN	April
DAWN	October
(null)	July
(null)	January

Codes – Encryption and Decryption

- Plaintext:
  - "ATTACK AT DAWN"
- Ciphertext:
  - "March September October" or
  - "March September April" or
  - "July December January September April July" or …
- Codewords can be random numbers, strings of characters, or other symbols

Types of Cryptosystems (cont)

- Symmetric-key
  - Same key used for encryption and decryption
  - Typically used for bulk encryption
- Asymmetric-key (or public-key)
  - Different key used for encryption and decryption
  - Usually not used for bulk encryption
- Hybrid cryptosystems

Symmetric-key Cryptosystems

- Standard use of a symmetric-key cryptosystem:
  - Sender and receiver agree on a secret key
    - Must be done securely!
  - Messages are encrypted by the sender with the shared key and decrypted by the receiver with the shared key
  - Note: Users need to have a previously-established shared secret to communicate securely

Public-Key Cryptosystems

- Standard use of a public-key cryptosystem:
  - Generate a public-key/private-key pair
    - Disseminate your public key widely
    - Keep your private key secret
  - Anybody can encrypt a message to you using your public key
  - Only you can decrypt the message using your private key

  - Note: unlike symmetric-key cryptosystems, users don’t need to have a previously-established shared secret to communicate securely

Public-Key Cryptosystems (cont)

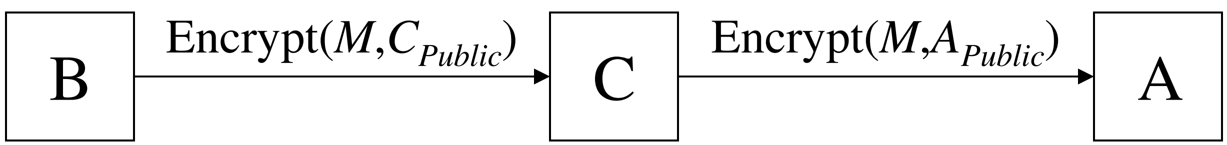
- Standard use of a public-key cryptosystem:
  - Digital signatures - proof of authorship of a document or agreement with its contents
    - User encrypts a document with his private key to create a digital signature
    - Anybody can verify the digital signature by using the signer’s public key
    - Only the signer can produce his signature, and he can’t reasonably claim he didn’t sign a document bearing his signature
  - Note: unlike symmetric-key cryptosystems, users can create authentic, unforgable, nonreusable, nonrepudiable digital signatures

Public-Key Cryptosystems (cont)

- In order for a public-key cryptosystem to work:
  - For every message, M, Decrypt(Encrypt(M, A_{Public}), $A_{Private}$) = M
  - For every pair of users, A and B, (A_{Public}, $A_{Private}$) and (B_{Public}, $B_{Private}$) must be distinct
  - Deriving $A_{private}$ from A_{Public} or the plaintext from the ciphertext is difficult
  - Key generation, encryption, and decryption routines must be relatively fast

Public-Key Cryptosystems - Problems

- Problem #1 - Man in the Middle:
  - Recall - everybody should know *A*'s public key
  - So if *B* wants to send a message, *M*, to *A* then *B* needs to encrypt *M* with A_{Public}
  - What if an adversary, *C*, is able to trick *B* into thinking that C_{Public} is A_{Public}?



  - *A* and *B* think their messages are secure, but *C* can read them
  - Public-key cryptography depends heavily on knowing to whom a public key belongs

Public-Key Cryptosystems - Problems

- Problem #2 - Known Ciphertext:
  - Recall - everybody should know *A*'s public key
  - So if *C* sees an encrypted message, Encrypt(M, A_{Public}) from *B* to *A*
    - C can choose a message, *M'*
    - Encrypt *M'* with *A*'s public key to get Encrypt(M', A_{Public})
    - Compare Encrypt(M', A_{Public}) with Encrypt(M, A_{Public}), if they match then *C* knows the message *B* sent to *A*
  - This is a serious problem if the number of possible plaintext messages is small enough to allow exhaustive search

Hybrid Cryptosystems

- Symmetric-key cryptosystems:
  - Good for bulk data, but require shared secrets
- Public-key cryptosystems:
  - Don’t require any shared secrets, but too slow for bulk encryption
- Hybrid cryptosystems:
  - Given a message *M*
  - Choose a key, *K*, at random to be used with a symmetric-key algorithm
  - Encrypt *K* with the recipient’s public key
  - Encrypt *M* with *K*
  - Send to recipient:

Encrypt(K, A_{Public})	Encrypt(M, K)

Hybrid Cryptosystems (cont)

- Hybrid cryptosystems:

Encrypt(K, A_{Public})	Encrypt(M, K)

  - Recipient decrypts first part of the message with his/her private key to learn K
  - Recipient uses K to decrypt the remainder of the message
  - Result: <u>Doesn’t require any shared secrets, and good for bulk encryption</u>

Summary

- **Cryptography** is the science of designing and analyzing cryptosystems which are used to disguise messages so that only certain people can see through the disguise
- **Cryptanalysis** is the science of attacking cryptosystems
- Classic cryptosystems include the **Caesar cipher**, **monoalphabetic replacement cipher**, and **one-time pad**
- **Symetric-key** cryptosystems are useful for bulk data encryption but required a shared secret
- **Public-key** cryptosystems are much slower but don’t require shared secrets and support digital signatures
- **Hybrid** cryptosystems are good for bulk encryption and don’t require any shared secrets