CS 5173/4173 Computer Security

Topic 2. Introduction to Cryptography

Cryptography

- *Cryptography*: the art of secret writing
- Converts data into unintelligible (random-looking) form
  - Must be *reversible* (can recover original data without loss or modification)
- If cryptography is combined with compression
  - What is the right order?

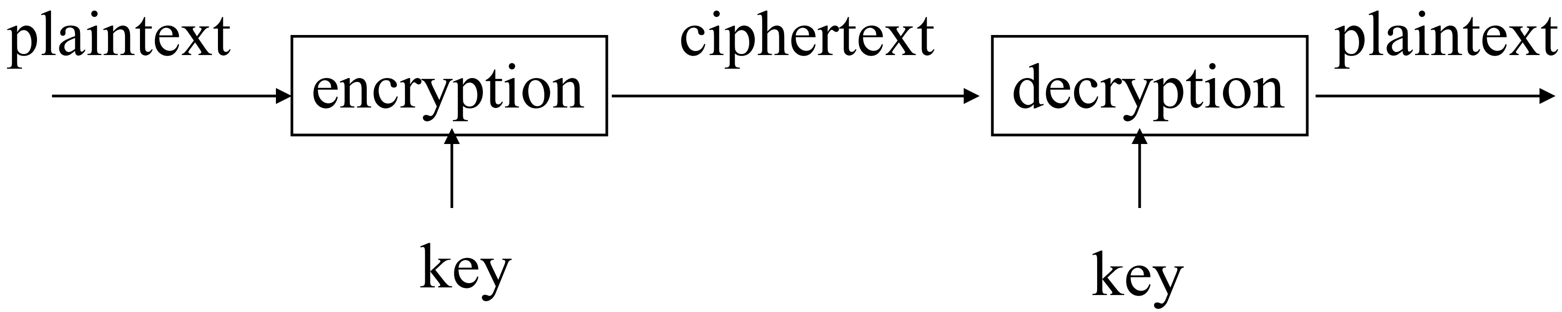
Cryptography vs. Steganography

- *Steganography* concerns existence
  - Conceals the very existence of communication
    - Examples?

> *Apparently neutral's protest is thoroughly discounted and ignored. Isman hard hit. Blockade issue affects pretext for embargo on by-poducts, ejecting suets and vegetable oils.*
>
> **Pershing sails from NY June I**

- *Cryptography* concerns what
  - Conceals the contents of communication between two parties

Encryption/Decryption



- Plaintext: a message in its original form
- Ciphertext: a message in the transformed, unrecognized form
- Encryption: the process that transforms a plaintext into a ciphertext
- Decryption: the process that transforms a ciphertext to the corresponding plaintext
- Key: the value used to control encryption/decryption.

Cryptanalysis

- Cryptanalysis: the art of revealing the secret
  - Defeat cryptographic security systems
  - Gain access to the real contents of encrypted messages
  - Cryptographic keys can be unknown
- Difficulty depends on
  - Sophistication of the encryption/decryption
  - Amount of information available to the code breaker

Ciphertext Only Attacks

- An attacker intercepts a set of ciphertexts
- Breaking the cipher: analyze patterns in the ciphertext
  - provides clues about the plaintext and key

Known Plaintext Attacks

- An attacker has samples of both the plaintext and its encrypted version, the ciphertext
- Makes some ciphers (e.g., mono-alphabetic ciphers) very easy to break

Chosen Plaintext Attacks

- An attacker has the capability to choose arbitrary plaintexts to be encrypted and obtain the corresponding ciphertexts
  – How could such attacks be possible?
  – Difference between known plaintext and chosen plaintext attacks

Exercise

- Alice wants to send a message to Bob. The message content is "sell the business".
- Alice encrypts the message by replacing each letter with the one 3 letters later in the alphabet (e.g., a -> d, b - > e)
  - What is the plaintext?
    - sell the business
  - What is the ciphertext?
    - vhoo wkh exvlqhvv
  - How to encrypt?
  - How to decrypt?
  - What is the key in this cryptosystem?
    - 3
  - Cryptanalysis attacks?

Perfectly Secure Ciphers

1. Ciphertext does not reveal any information about which plaintexts are more likely to have produced it
   - e.g., the cipher is robust against ciphertext only attacks

and

2. Plaintext does not reveal any information about which ciphertexts are more likely to be produced
   - e.g, the cipher is robust against known/chosen plaintext attacks

Computationally Secure Ciphers

1. The cost of breaking the cipher quickly exceeds the value of the encrypted information

and/or

2. The time required to break the cipher exceeds the useful lifetime of the information

- Under the assumption there is not a faster / cheaper way to break the cipher, waiting to be discovered

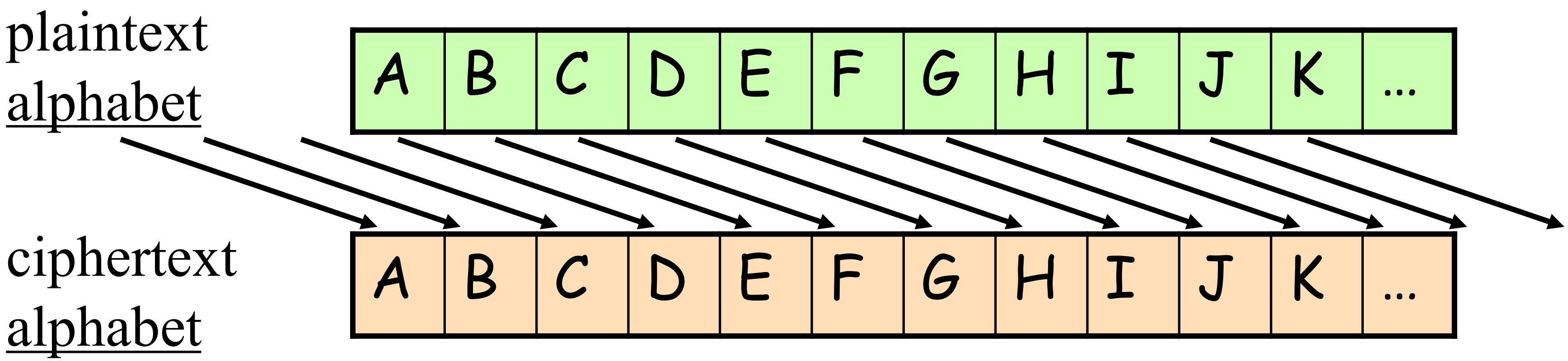
Secret Keys v.s. Secret Algorithms

- Keep algorithms secret
  - We can achieve better security if we keep the algorithms secret
  - Hard to keep secret if used widely
- Publish the algorithms
  - Security depends on the secrecy of the keys
  - Less unknown vulnerability if all the smart (good) people in the world are examine the algorithms
- Military
  - Both secret key and secret algorithm

Some Early Ciphers

Caesar Cipher

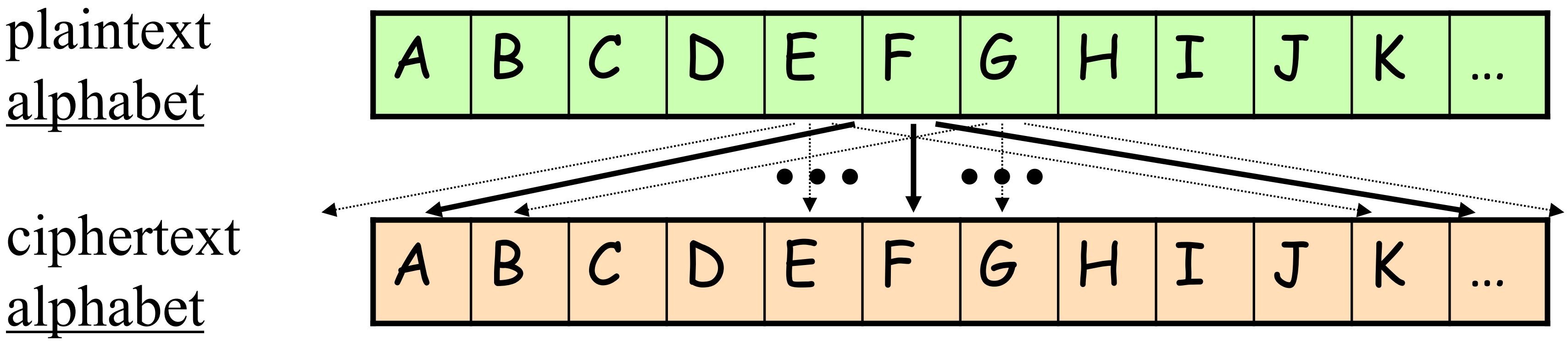
- Replace each letter with the one 3 letters later in the alphabet



Trivial to break

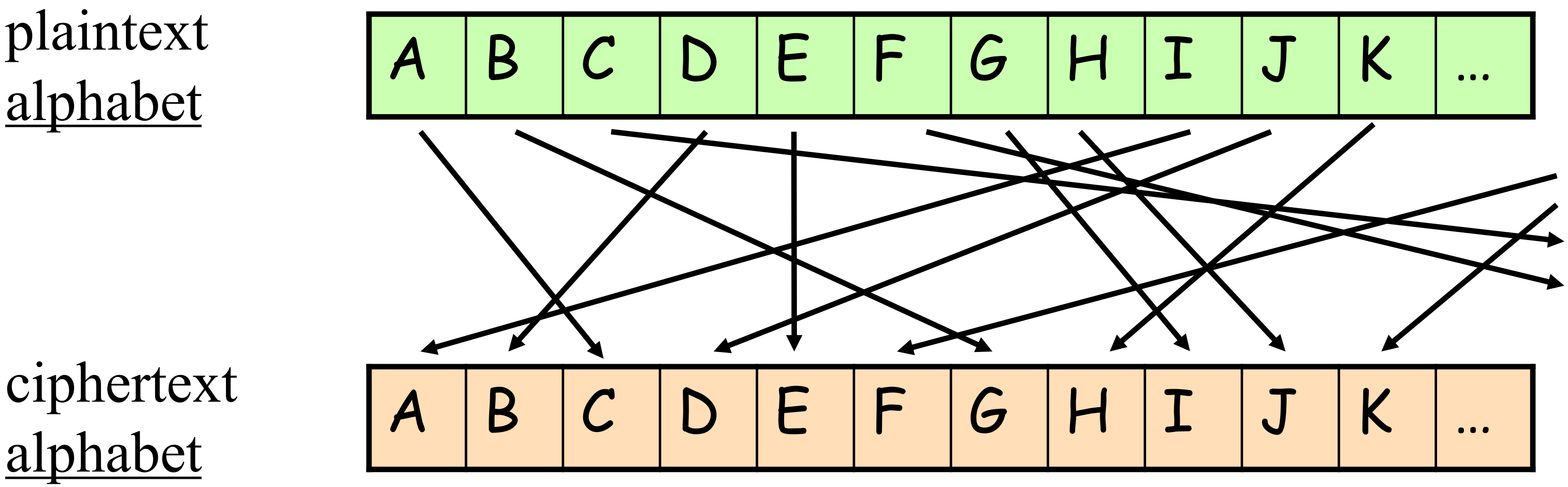
A variant of Caesar Cipher

- Replace each letter by one that is δ positions later, where δ is selectable (i.e., δ is the key)
  - example: IBM → HAL (for δ=25)
- Also trivial to break with modern computers (how many possibilities?)



Mono-Alphabetic Ciphers

- Generalized substitution cipher: randomly map one letter to another (How many possibilities?)
  – 26! ($\approx 4.0*10^{26} \approx 2^{88}$)
- The key must specify which permutation; how many bits does that take?
  – $\log_2(26!)$ ($\approx$ 90 bits)



Attacking Mono-Alphabetic Ciphers

- Known plaintext attacks
- Frequency of single letters in English language, taken from a large corpus of text:

A ≈ 8.2%	H ≈ 6.1%	O ≈ 7.5%	V ≈ 1.0%
B ≈ 1.5%	I ≈ 7.0%	P ≈ 1.9%	W ≈ 2.4%
C ≈ 2.8%	J ≈ 0.2%	Q ≈ 0.1%	X ≈ 0.2%
D ≈ 4.3%	K ≈ 0.8%	R ≈ 6.0%	Y ≈ 2.0%
E ≈ 12.7%	L ≈ 4.0%	S ≈ 6.3%	Z ≈ 0.1%
F ≈ 2.2%	M ≈ 2.4%	T ≈ 9.1%	
G ≈ 2.0%	N ≈ 6.7%	U ≈ 2.8%	

Attacking… (Cont'd)

- Suppose the attacker intercepts the following message

UXGPOGZCFJZJTFADADAJEJNDZMZHBBGZGGKQGVVGXCDIWGX

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
3	2	2	4	1	2	8	1	1	4	1	0	1	1	1	1	1	0	0	1	1	2	1	3	0	5

A ≈ 8.2%	H ≈ 6.1%	O ≈ 7.5%	V ≈ 1.0%
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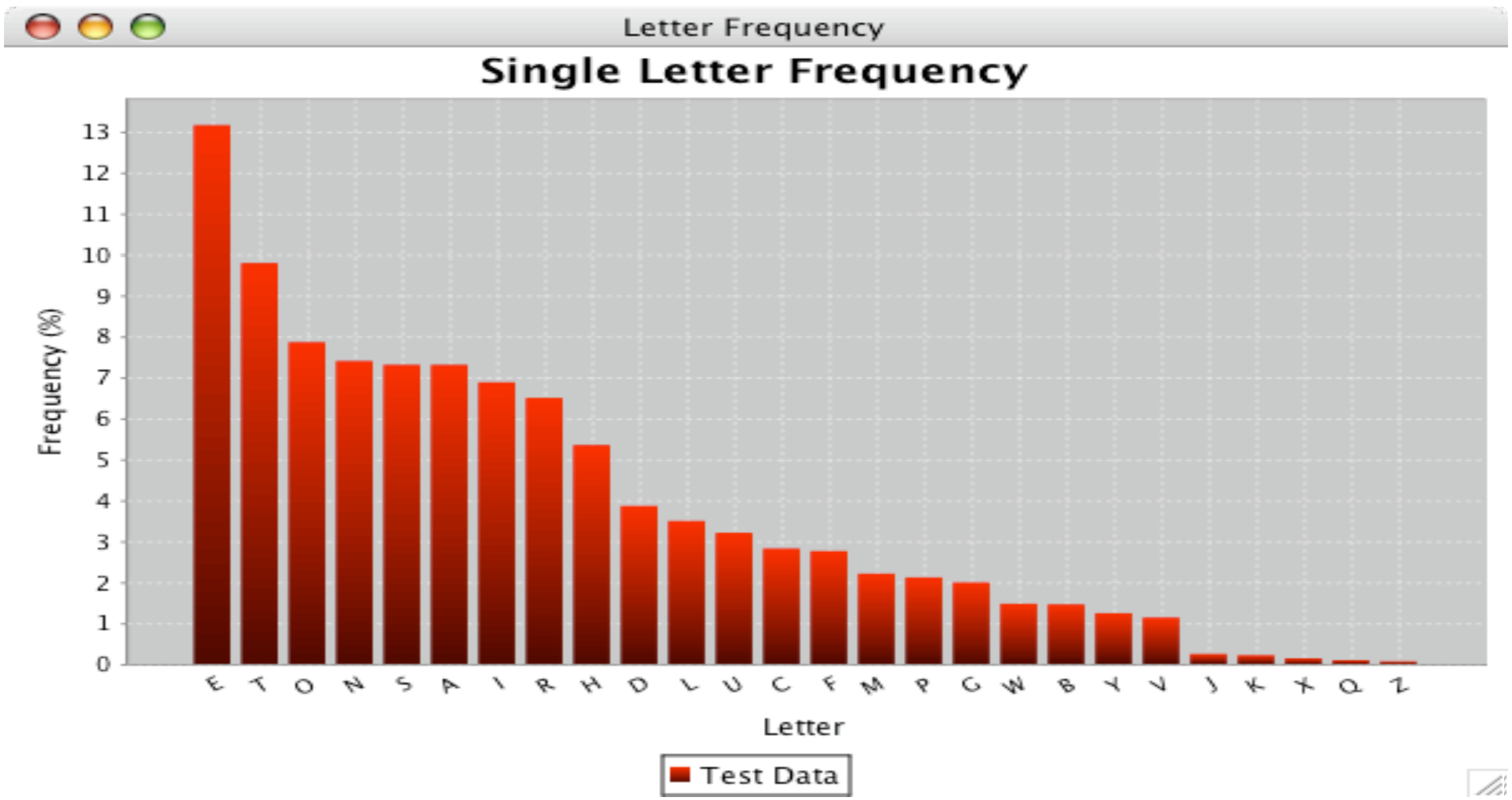
FREQUENCY ANALYSIS IS AMAZING NOW WE NEED BETTER CIPHER

Letter Frequencies



Vigenere Cipher

- A set of mono-alphabetic substitution rules (shift amounts) is used
  - the key determines what the sequence of rules is
  - also called a *poly-alphabetic* cipher
- Ex.: key = (3 1 5)
  - i.e., substitute first letter in plaintext by letter+3, second letter by letter+1, third letter by letter+5
  - then repeat this cycle for each 3 letters

Vigenere… (Cont'd)

- Ex.: plaintext = "BANDBAD"

plaintext message

B	A	N	D	B	A	D

shift amount

3	1	5	3	1	5	3

ciphertext message

E	B	S	G	C	F	G

What are the possible attacks?

- Known plaintext? Frequency analysis?

Hill Ciphers

- Encrypts *m* letters of plaintext at each step
  - i.e., plaintext is processed in blocks of size *m*
- Encryption of plaintext p to produce ciphertext c is accomplished by: $c = \boldsymbol{K}p$
  - the $m \times m$ matrix $\boldsymbol{K}$ is the key
  - decryption is multiplication by inverse: $p = \boldsymbol{K}^{-1}c$
  - *remember: all arithmetic mod 26*

Hill Cipher Example

- For $m = 2$, let $K = \begin{matrix} 1 & 2 \\ 3 & 5 \end{matrix}$, $K^{-1} = \begin{matrix} 21 & 2 \\ 3 & 25 \end{matrix}$

Plaintext p =

A	B	X	Y	D	G
0	1	23	24	3	6

(21*15+2*13) mod 26

(1*0+2*1) mod 26

(3*23+5*24) mod 26

Ciphertext c =

2	5	19	7	15	13
C	F	T	H	P	N

What about encrypting "CS"?

Hill… (Cont'd)

- Fairly strong for large m
- Possible attacks
  - Ciphertext only?
  - Known/Chosen plaintext attack?
    - Choose m plaintexts, generate corresponding ciphertexts
    - Form a m x m matrix $\boldsymbol{X}$ from the plaintexts, and m x m matrix $\boldsymbol{Y}$ from the ciphertexts
    - Can solve directly for $\boldsymbol{K}$ (i.e., $\boldsymbol{K} = \boldsymbol{Y}\,\boldsymbol{X}^{-1}$)
    - How many (plaintext, ciphertext) pairs are required?

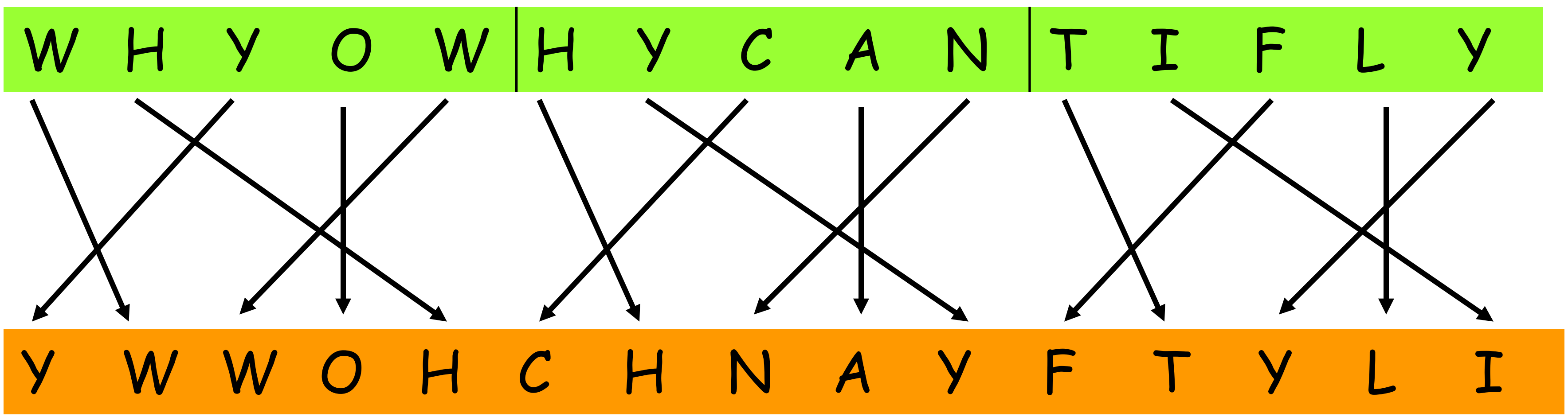
Permutation Ciphers

- The previous codes are all based on substituting one symbol in the alphabet for another symbol in the alphabet
- Permutation cipher: permute (rearrange, transpose) the letters in the message
  - the permutation can be fixed, or can change over the length of the message

Permutation… (Cont'd)

- Permutation cipher ex. #1:
  - Permute each successive block of 5 letters in the message according to position offset <+1,+3,-2,0,-2>

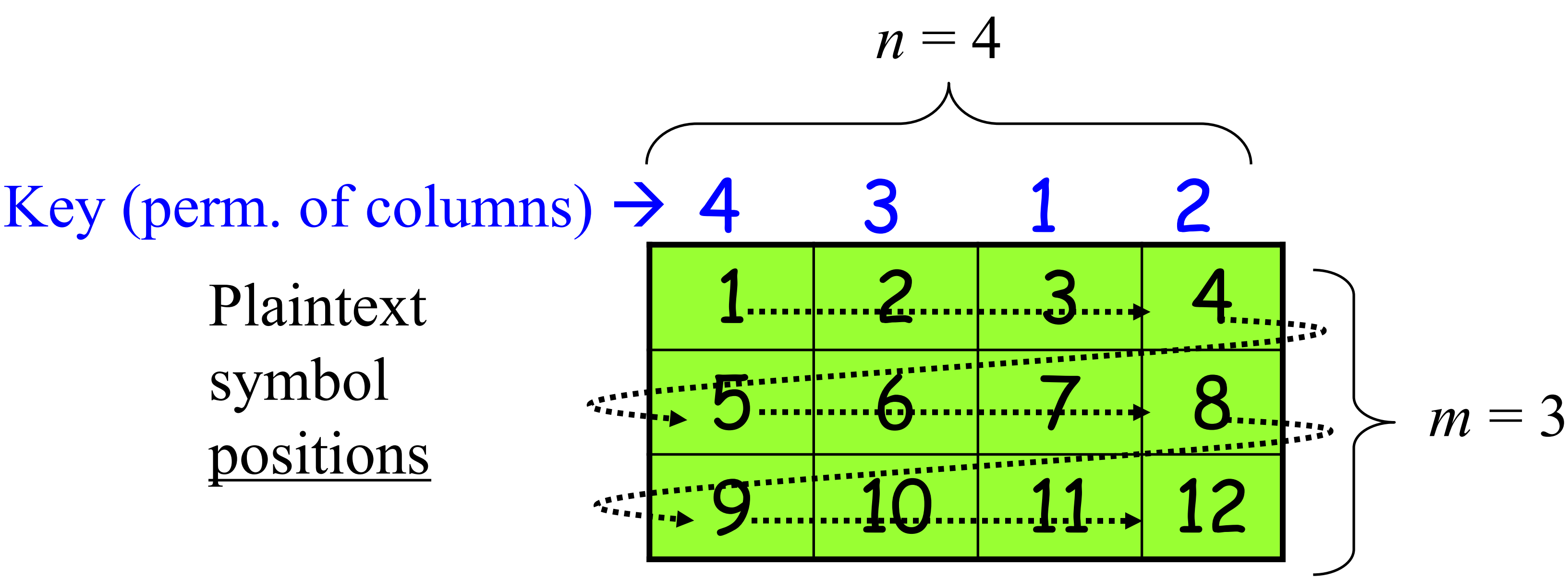
plaintext message



ciphertext message

Permutation… (Cont’d)

- Permutation cipher ex. #2:
- arrange plaintext in blocks of n columns and m rows
- then permute columns in a block according to a key K



ciphertext sequence (by plaintext position) for one block

3	7	11	4	8	12	2	6	10	1	5	9

Permutation… (Cont'd)

- A longer example: plaintext = "ATTACK POSTPONED UNTIL TWO AM"

Key:	4	3	1	2	5	7	6
plaintext	A	T	T	A	C	K	P
	O	S	T	P	O	N	E
	D	U	N	T	I	L	T
	W	O	A	M	X	Y	Z

ciphertext

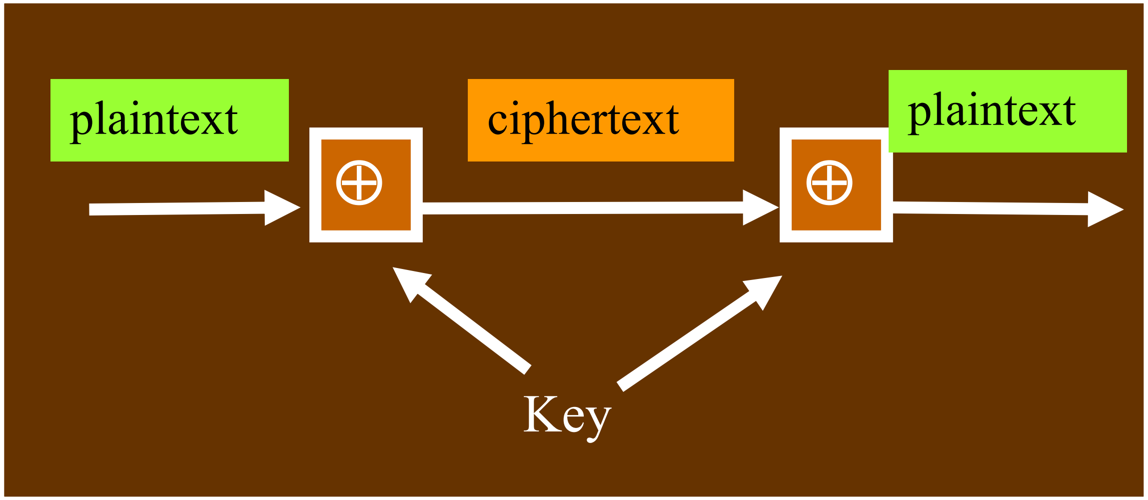
TTNA APTM TSUO AODW COIX PETZ KNLY

A Perfectly Secure Cipher: One-Time Pads

- According to a theorem by Shannon, a perfectly secure cipher requires:
  - a key length at least as long as the message to be encrypted
  - the key can only be used once (i.e., for each message we need a new key)
- Very limited use due to need to negotiate and distribute long, random keys for every message

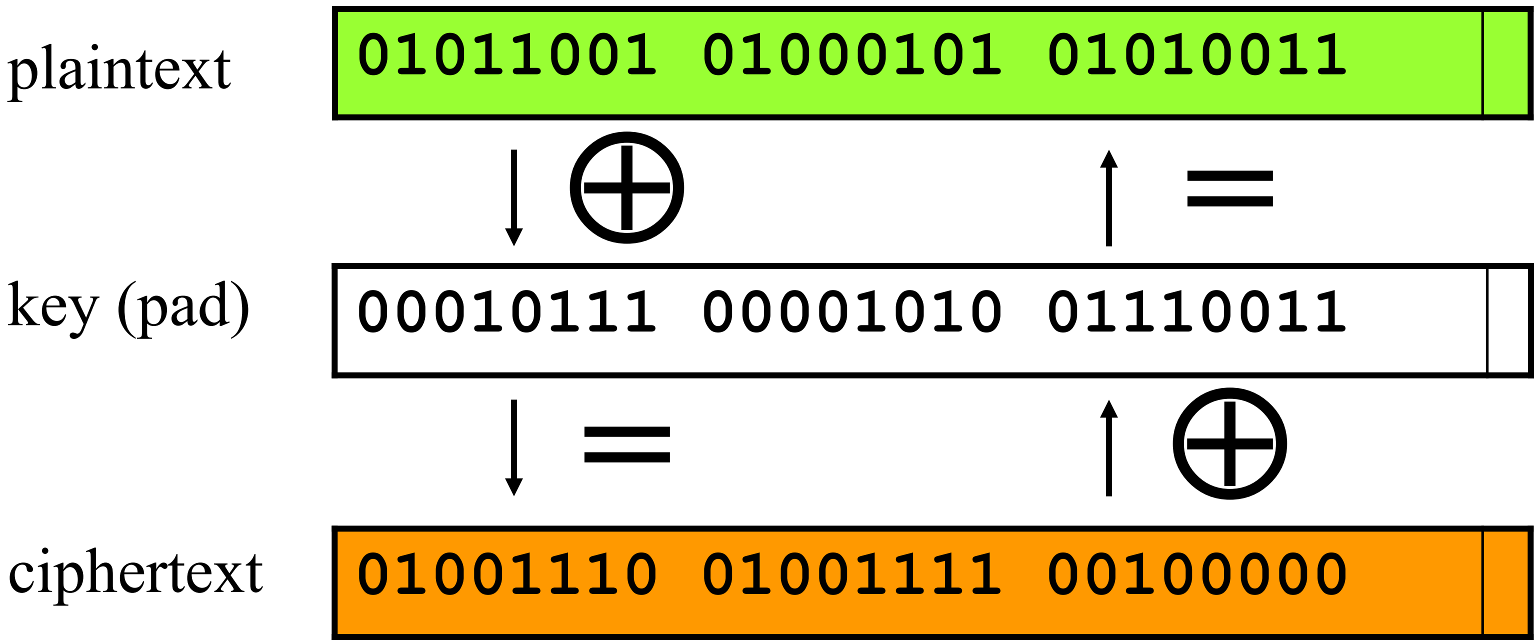
OTP… (Cont'd)

- Idea
  - generate a random bit string (the key) as long as the plaintext, and share with the other communicating party
  - encryption: XOR this key with plaintext to get ciphertext
  - decrypt: XOR same key with ciphertext to get plaintext



$$
\begin{aligned}
0 \oplus 0 &= 0 \\
0 \oplus 1 &= 1 \\
1 \oplus 0 &= 1 \\
1 \oplus 1 &= 0
\end{aligned}
$$

OTP… (Cont’d)



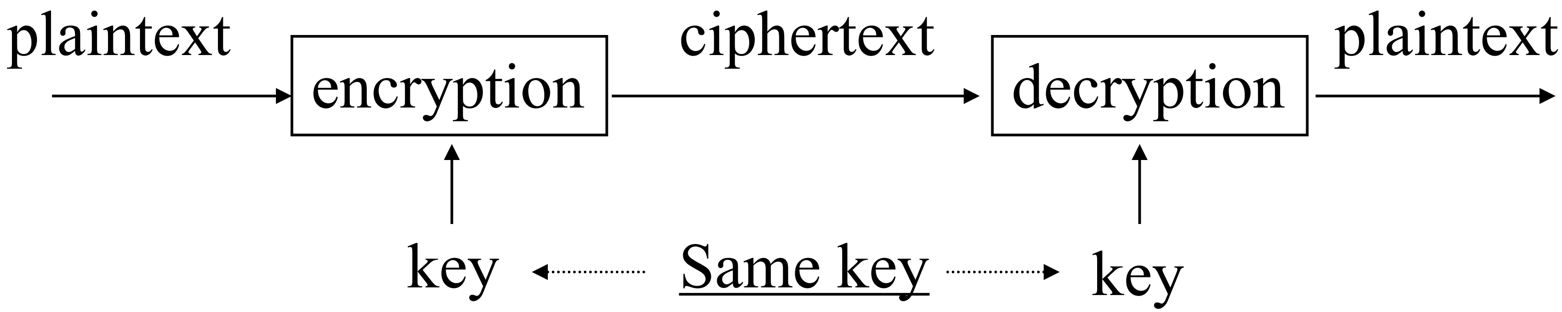
- Why can’t the key be reused?
  - if $C = P \oplus K$, then $K = C \oplus P$

Some “Key” Issues

Types of Cryptography

- Number of keys
  - Hash functions: no key
  - Secret key cryptography: one key
  - Public key cryptography: two keys - public, private
- The way in which the plaintext is processed
  - Stream cipher: encrypt input message one symbol at a time
  - Block cipher: divide input message into blocks of symbols, and processes the blocks in sequence
    - May require padding

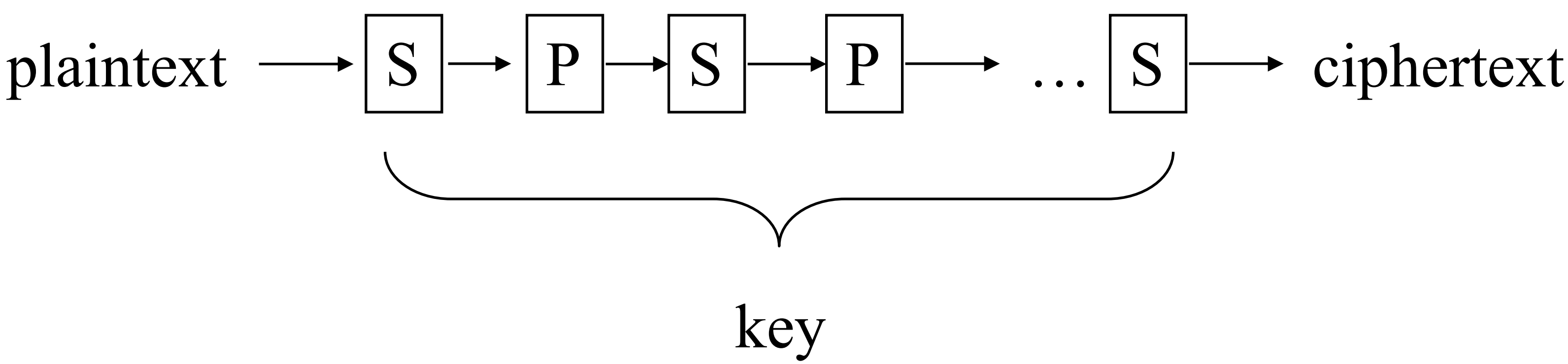
Secret Key Cryptography



- Same key is used for encryption and decryption
- Also known as
  - Symmetric cryptography
  - Conventional cryptography

Secret Key Cryptography (Cont'd)

- Basic technique
  - Product cipher:
    - Multiple applications of interleaved substitutions and permutations



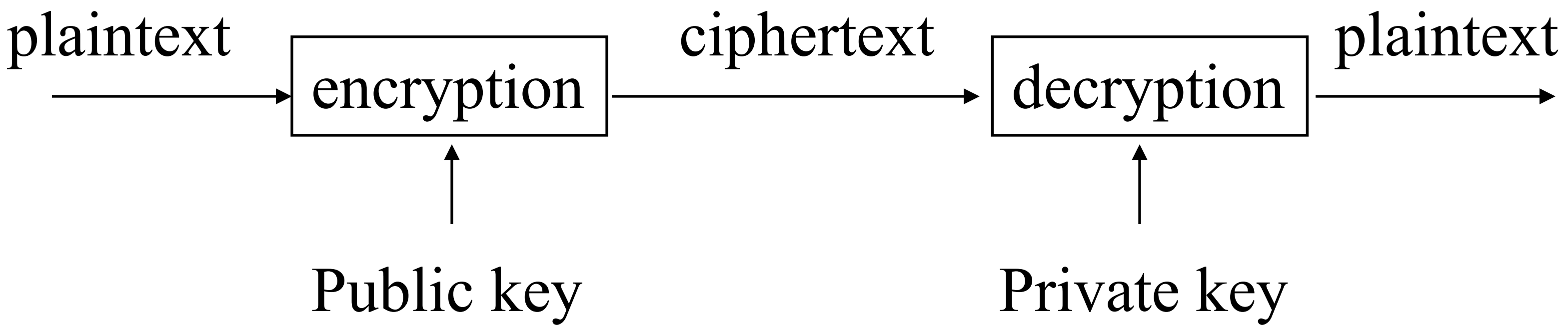
Secret Key Cryptography (Cont’d)

- Ciphertext approximately the same length as plaintext
- Examples
  - Stream Cipher: RC4
  - Block Cipher: DES, IDEA, AES

Applications of Secret Key Cryptography

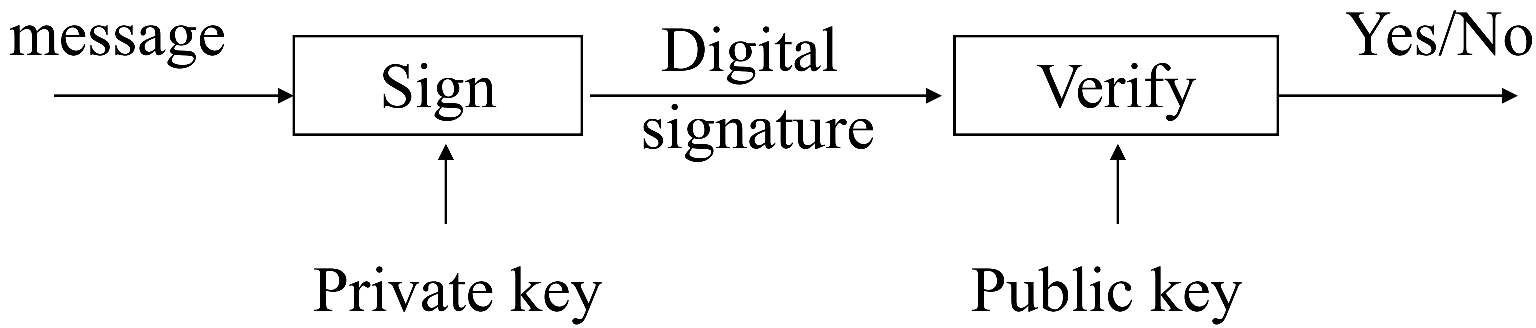
- Transmitting over an insecure channel
  - Challenge: How to share the key?
- Authentication
  - Challenge-response
  - To prove the other party knows the secret key
  - Must be secure against chosen plaintext attack
- Integrity check
  - Message Integrity Code (MIC)
    - a.k.a. Message Authentication Code (MAC)

Public Key Cryptography



- Invented/published in 1975
- A public/private key pair is used
  - Public key can be publicly known
  - Private key is kept secret by the owner of the key
- Much slower than secret key cryptography
- Also known as
  - Asymmetric cryptography

Public Key Cryptography (Cont'd)



- Another mode: digital signature
  - Only the party with the private key can create a digital signature.
  - The digital signature is verifiable by anyone who knows the public key.
  - The signer cannot deny that he/she has done so.

Applications of Public Key Cryptography

- Data transmission:
  - Alice encrypts m_a using Bob's public key e_B, Bob decrypts m_a using his private key d_B.
- Storage:
  - Can create a safety copy: using public key of trusted person.
- Authentication:
  - No need for verifiers to store secrets, only need public keys.
  - Secret key cryptography: need to share secret key for every person to communicate with.

Applications of Public Key Cryptography (Cont’d)

- Digital signatures
  - Sign hash $H(m)$ with the private key
    - Authorship
    - Integrity
    - Non-repudiation: can’t do with secret key cryptography
- Key exchange
  - Establish a common session key between two parties
  - Particularly for encrypting long messages

Hash Algorithms

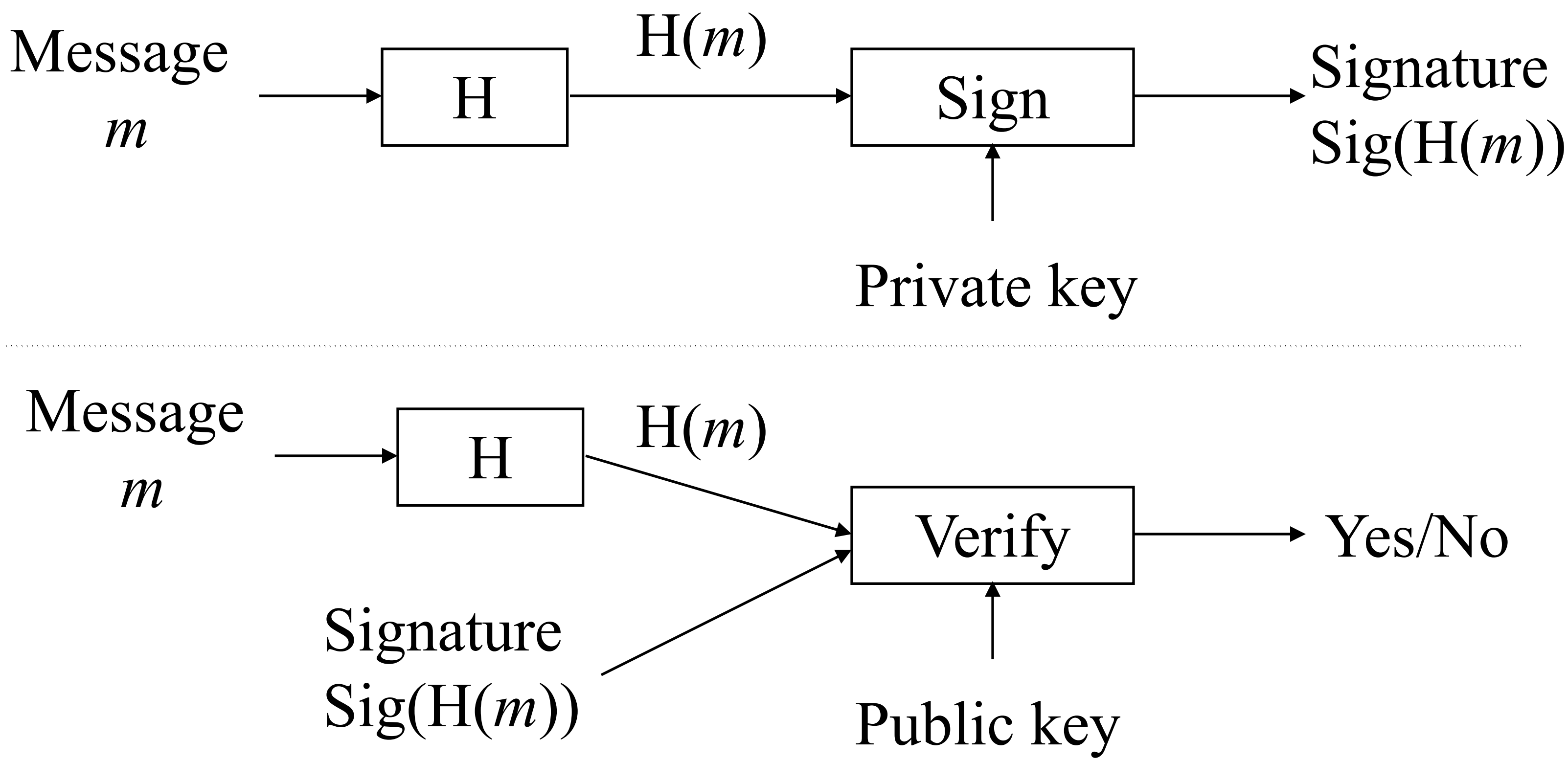
- Also known as
  - Message digests
  - One-way transformations
  - One-way functions
  - Hash functions
- Length of $H(m)$ much shorter then length of m
- Usually fixed lengths: 128 or 160 bits

Hash Algorithms (Cont'd)

- Desirable properties of hash functions
  - Performance: Easy to compute $H(m)$
  - One-way property: Given $H(m)$ but not m, it's difficult to find m
  - Weak collision free: Given $H(m)$, it's difficult to find m' such that $H(m') = H(m)$.
  - Strong collision free: Computationally infeasible to find m_1, m_2 such that $H(m_1) = H(m_2)$

Applications of Hash Functions

- Primary application
  - Generate/verify digital signatures



Applications of Hash Functions (Cont’d)

- Password hashing
  - Doesn’t need to know password to verify it
  - Store *H*(*password*+*salt*) and salt, and compare it with the user-entered password
  - Salt makes dictionary attack more difficult
- Message integrity
  - Agree on a secrete key *k*
  - Compute *H*(*m*|*k*) and send with *m*
  - Doesn’t require encryption algorithm, so the technology is exportable

Applications of Hash Functions (Cont’d)

- Message fingerprinting
  - Verify whether some large data structures (e.g., a program) has been modified
  - Keep a copy of the hash
  - At verification time, recompute the hash and compare

  - Hashing program and the hash values must be protected separately from the large data structures

Summary

- Cryptography is a fundamental, and most carefully studied, component of security
  - not usually the “weak link”
- “Perfectly secure” ciphers are possible, but too expensive in practice
- Early ciphers aren’t nearly strong enough
- Key distribution and management is a challenge for any cipher