CSCI 454/554 Computer and Network Security

Topic 2. Introduction to Cryptography

Outline

- Basic Crypto Concepts and Definitions
- Some Early (Breakable) Cryptosystems
- "Key" Issues

Basic Concepts and Definitions

Cryptography

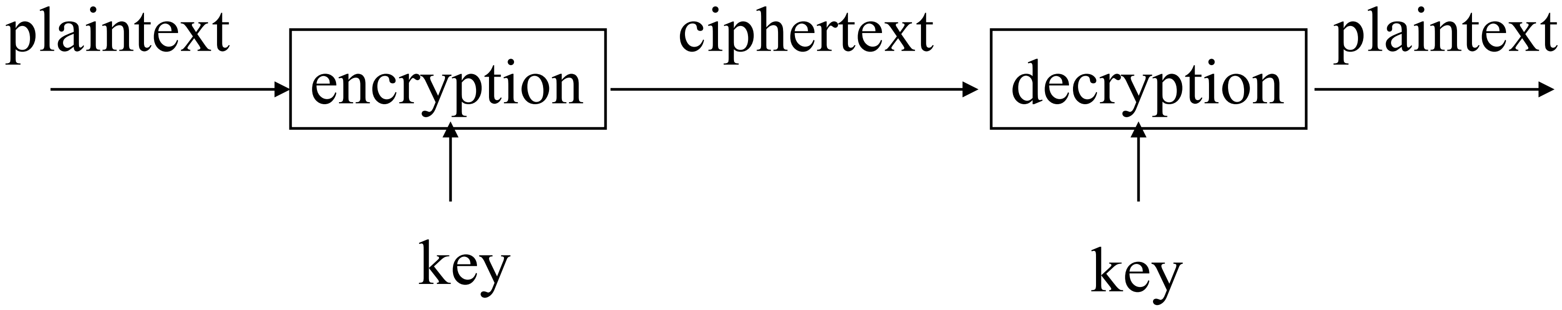
- *Cryptography*: the art of secret writing
- Converts data into unintelligible (random-looking) form
  - Must be *reversible* (can recover original data without loss or modification)
- Not the same as compression
  - *n* bits in, *n* bits out
  - Can be combined with compression
    - What's the right order?

Cryptography vs. Steganography

- *Cryptography* conceals the contents of communication between two parties
- *Anonymous communication* conceals who is communicating
- Kerckhoffs's principle
  - A cryptosystem should be secure even if everything about the system, except the key, is public knowledge

- *Steganography* (hiding in plain sight) conceals the very existence of communication
  - Examples?
    - Watermark
    - Info leakage
- Security through obscurity
  - Defense in depth
  - Open source software?

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

- “code breaking”, “attacking the cipher”
- Difficulty depends on
  - sophistication of the cipher
  - amount of information available to the code breaker
- Any cipher can be broken by exhaustive trials, but rarely practical
  - When can you recognize if you have succeeded?

Ciphertext Only Attacks

- Ex.: attacker can intercept encrypted communications, nothing else
  - when is this realistic?
- Breaking the cipher: analyze patterns in the ciphertext
  - provides clues about the encryption method/key

Known Plaintext Attacks

- Ex.: attacker intercepts encrypted text, but also has access to some of the corresponding plaintext (definite advantage)
    - When is this realistic?
- Requires plaintext-ciphertext pairs to recover the key, but the attacker cannot choose which particular pairs to access.
    - Makes some codes (e.g., mono-alphabetic ciphers) very easy to break

Chosen Plaintext Attacks

- Ex.: attacker can choose any plaintext desired, and intercept the corresponding ciphertext
  - When is this realistic?

- Choose exactly the messages that will reveal the most about the cipher

Chosen Ciphertext Attacks

- Ex.: attacker can present any ciphertext desired to the cipher, and get the corresponding plaintext
  - When is this realistic?
- Isn't this the goal of cryptanalysis???

The “Weakest Link” in Security

- Cryptography is rarely the weakest link
- Weaker links
  - Implementation of cipher
  - Distribution or protection of keys

Perfectly Secure Ciphers

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

and

2. Plaintext does not reveal any information about which ciphertexts are more likely to be produced
    - i.e, the cipher is robust against 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 vs. Secret Algorithms

- Security by obscurity
  - We can achieve better security if we keep the algorithms secret
  - Hard to keep secret if used widely
  - Reverse engineering, social engineering
- Publish the algorithms
  - Security of the algorithms depends on the secrecy of the keys
  - Less unknown vulnerability if all the smart (good) people in the world are examine the algorithms

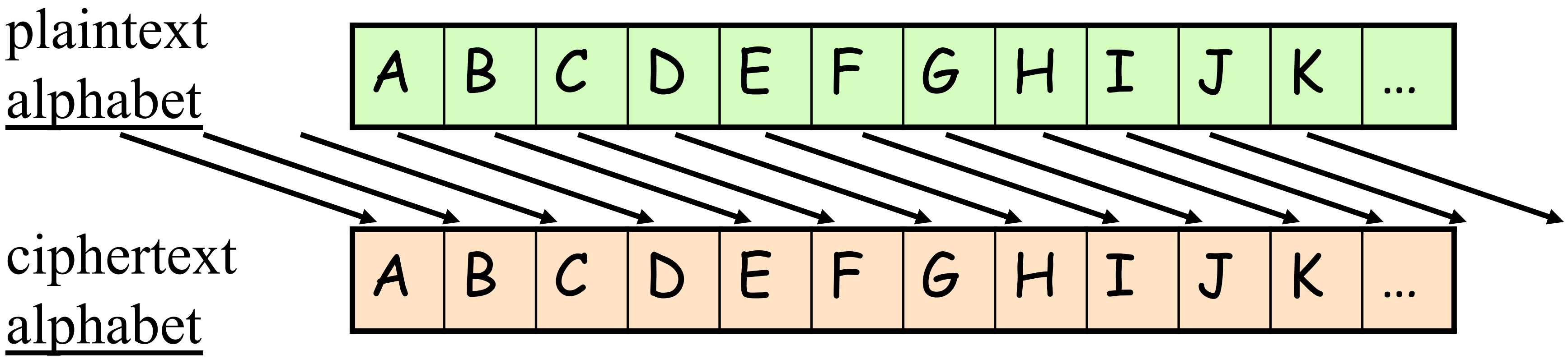
Secret Keys vs. Secret Algorithms

- Commercial world
  - Published
  - Wide review, trust
- Military
  - Keep algorithms secret
  - Avoid giving enemy good ideas
  - Military has access to the public domain knowledge anyway.

Some Early Ciphers

Caesar Cipher

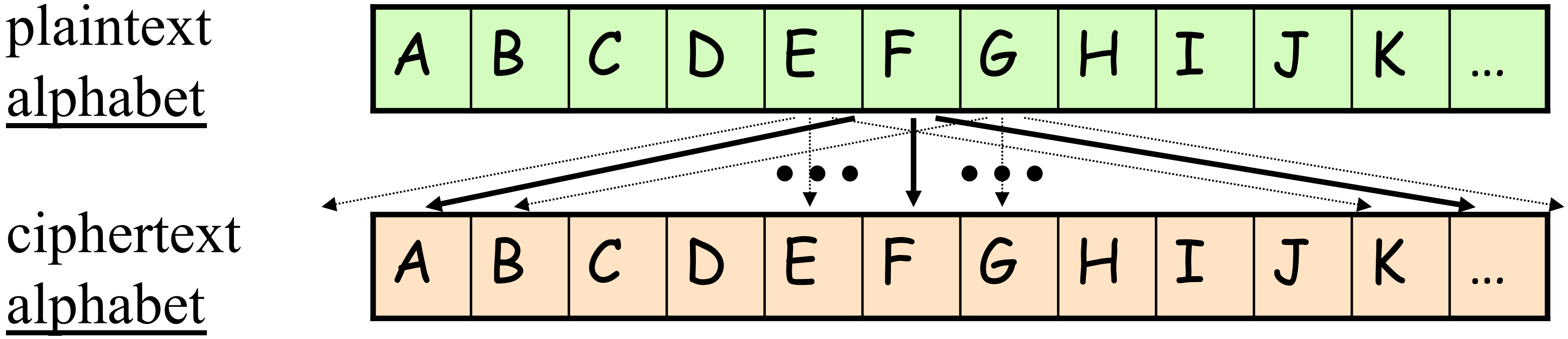
- Replace each letter with the one 3 letters later in the alphabet
  - ex.: plaintext CAT → ciphertext FDW



Trivial to break

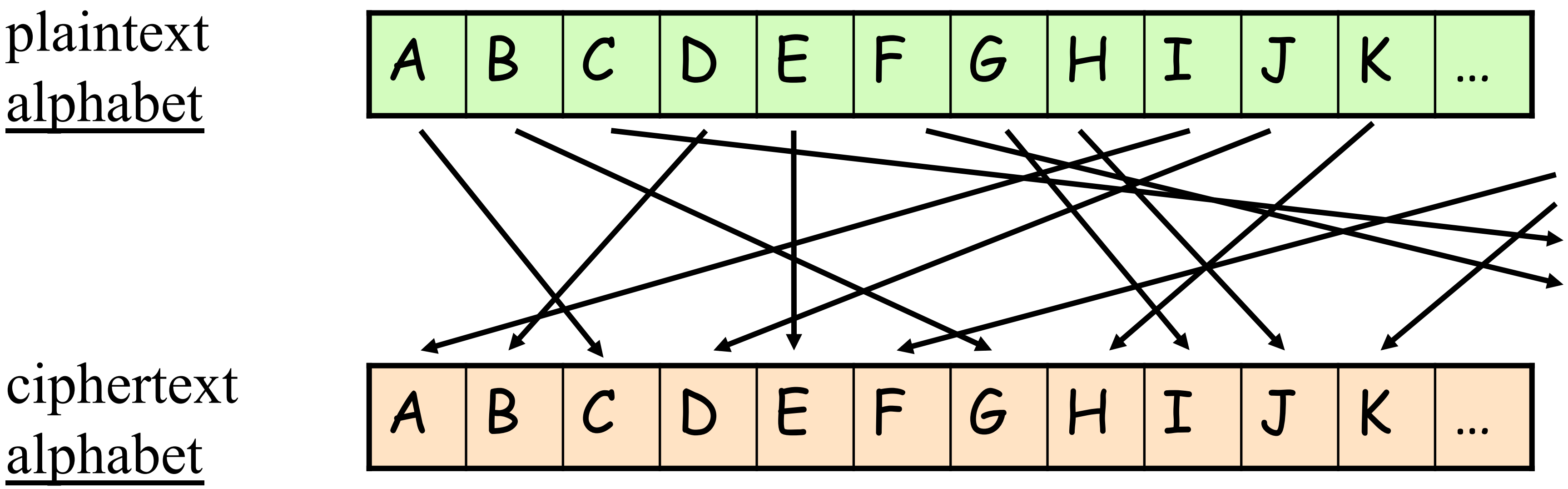
“Captain Midnight Secret Decoder” Ring

- 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 (only 26 possibilities)



Mono-Alphabetic Ciphers

- Generalized substitution cipher: an arbitrary (but fixed) mapping of one letter to another
  - 26! ($\approx 4.0*10^{26} \approx 2^{88}$) possibilities
- The key must specify which permutation; how many bits does that take?



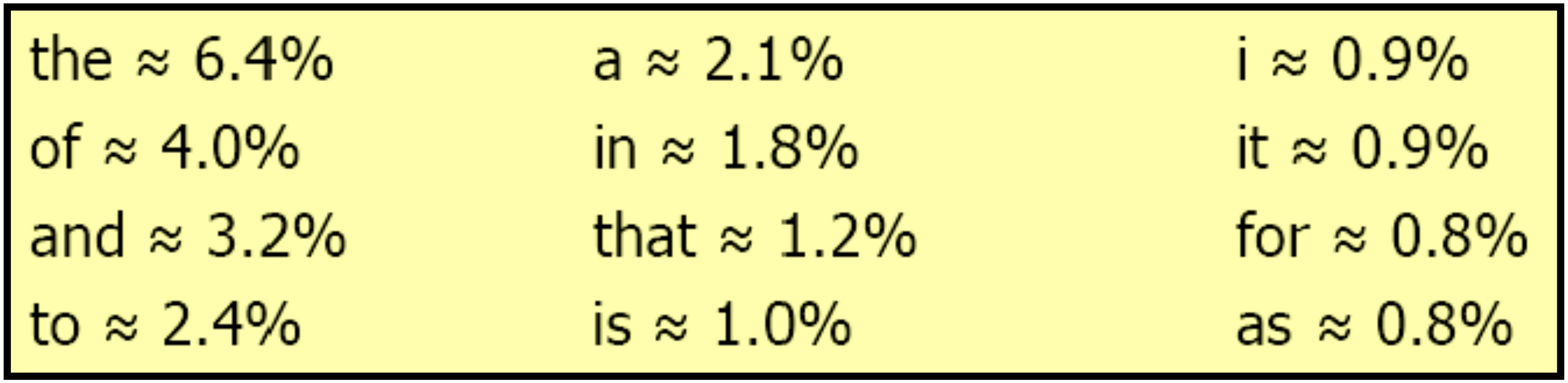
Attacking Mono-Alphabetic Ciphers

- Broken by statistical analysis of letter, word, and phrase frequencies of the language
- Frequency of single letters in English language, taken from a large corpus of text:

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

Attacking… (Cont'd)

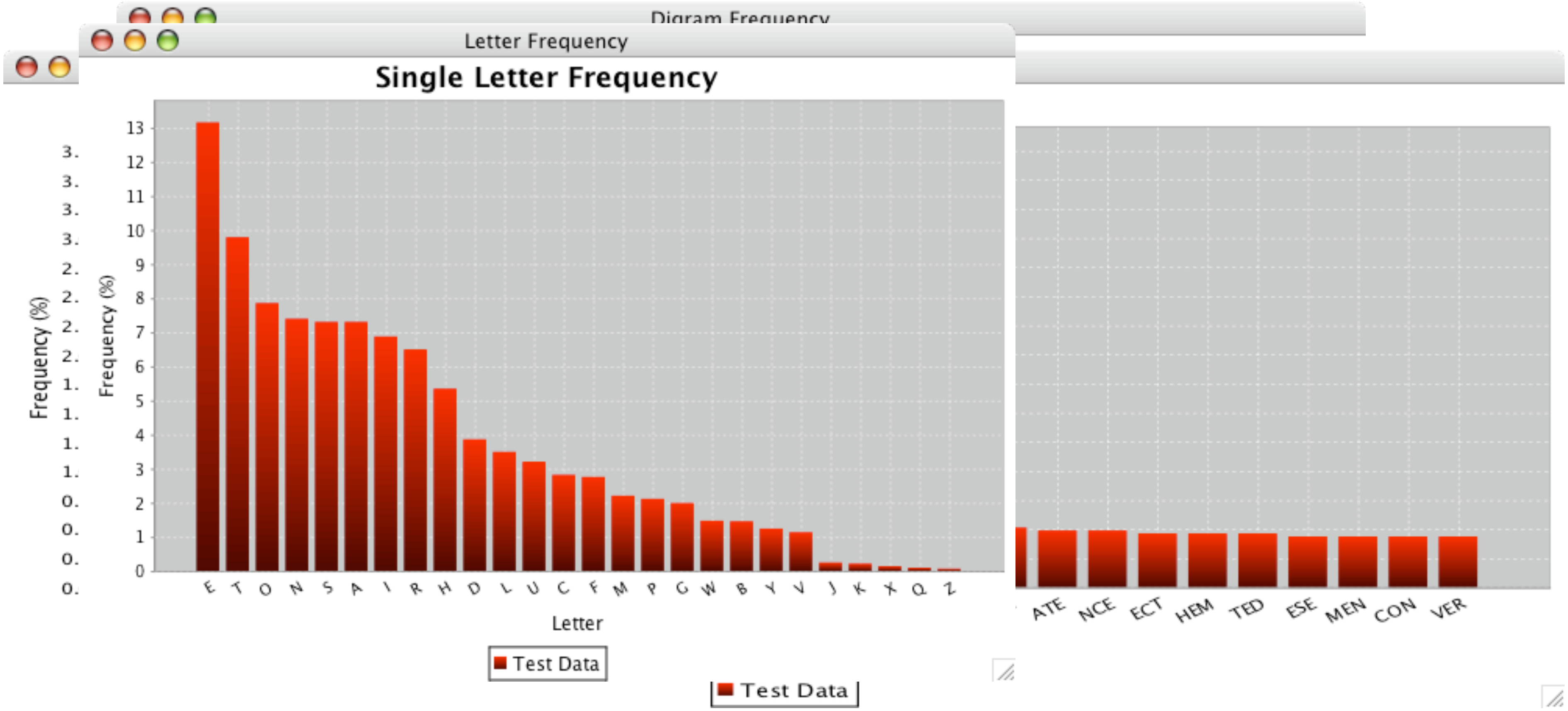
- If all words equally likely, probability of any one word would be quite low
  - how many words are there in the English language?
- Actual frequencies of some words in English language:



the ≈ 6.4%
of ≈ 4.0%
and ≈ 3.2%
to ≈ 2.4%
a ≈ 2.1%
in ≈ 1.8%
that ≈ 1.2%
is ≈ 1.0%
i ≈ 0.9%
it ≈ 0.9%
for ≈ 0.8%
as ≈ 0.8%

(Tip: Counting Letter Frequencies)

- Program `letter`, written by TJ O'Connor
- Output for Declaration of Independence:



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

Breaking the cipher: look for repeated patterns in the ciphertext

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 ***K*** is the key
    - ***K***'s determinant must be relatively prime to size of alphabet (26 for our example)
    - 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

Hill… (Cont’d)

- Fairly strong for large *m*
- But, vulnerable to chosen plaintext attack
  - choose *m* plaintexts, generate corresponding ciphertexts
  - form a *m* x *m* matrix ***X*** from the plaintexts, and *m* x *m* matrix ***Y*** from the ciphertexts (details omitted)
  - can solve directly for ***K*** (i.e., $K = Y X^{-1}$)

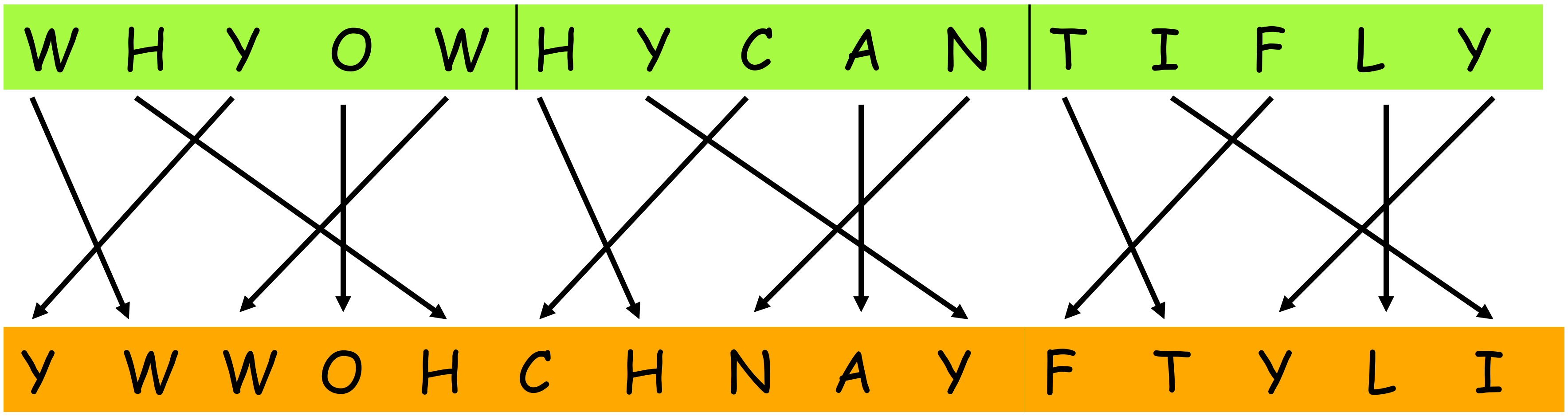
Permutation Ciphers

- 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>

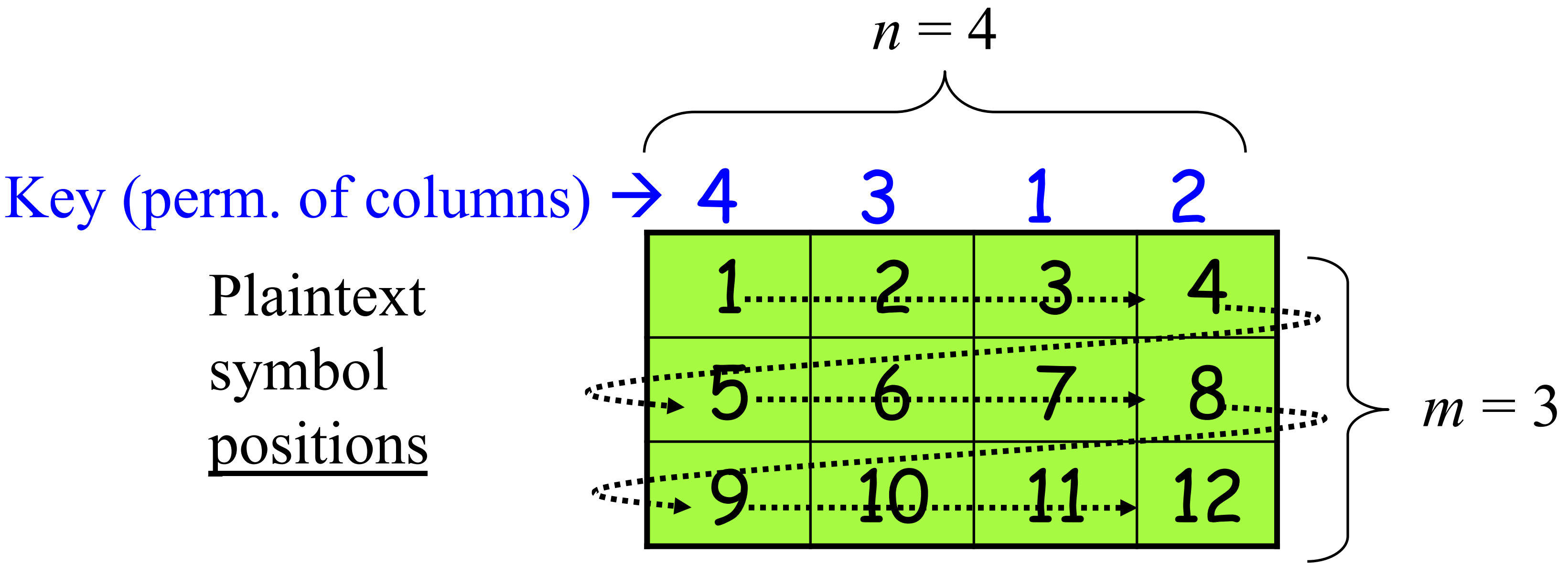
plaintext message



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



$n = 4$

Key (perm. of columns) →

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

Plaintext symbol positions

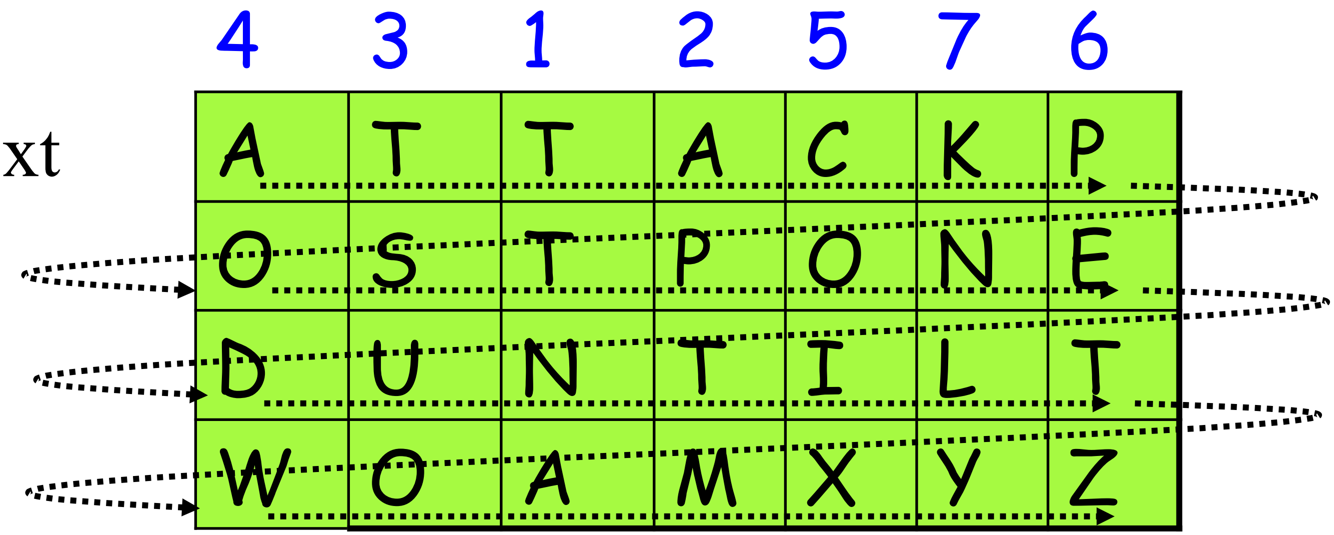
$m = 3$

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

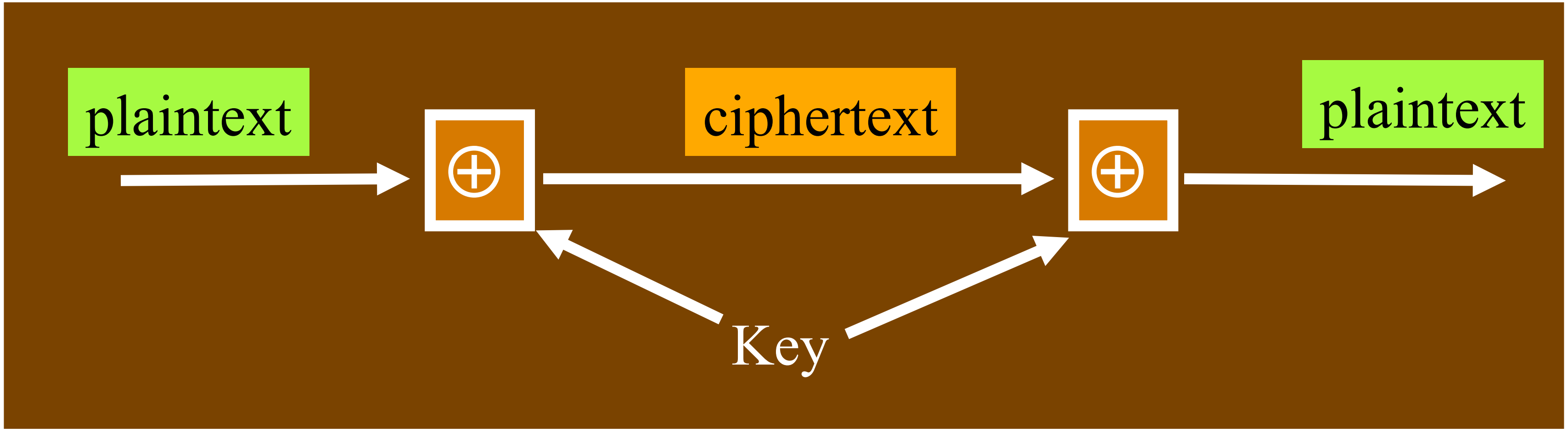
TTNA APTM TSUO AODW COIX PETZ KNLY

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



plaintext

⊕

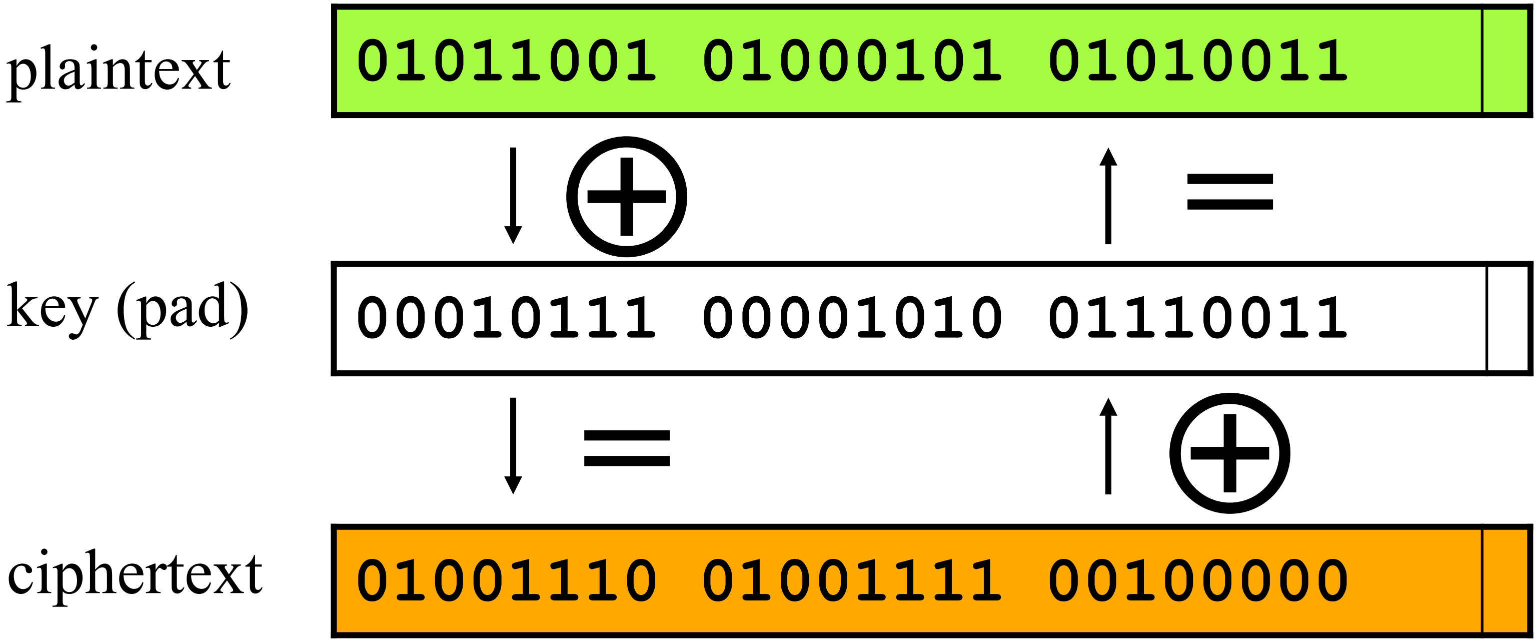
ciphertext

⊕

plaintext

Key

OTP… (Cont'd)



plaintext `01011001 01000101 01010011`

↓ ⊕ ↑ =

key (pad) `00010111 00001010 01110011`

↓ = ↑ ⊕

ciphertext `01001110 01001111 00100000`

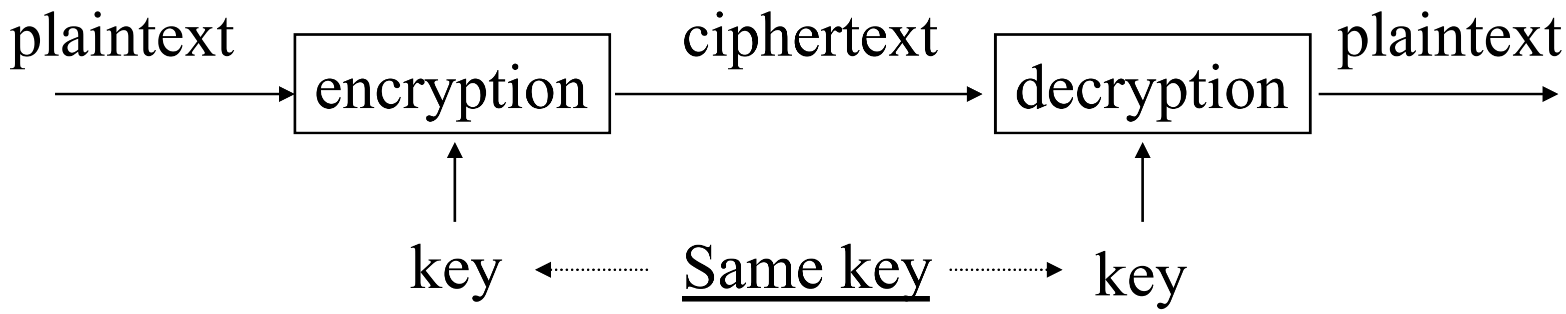
- Why can't the key be reused?

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


plaintext → encryption → ciphertext → decryption → plaintext

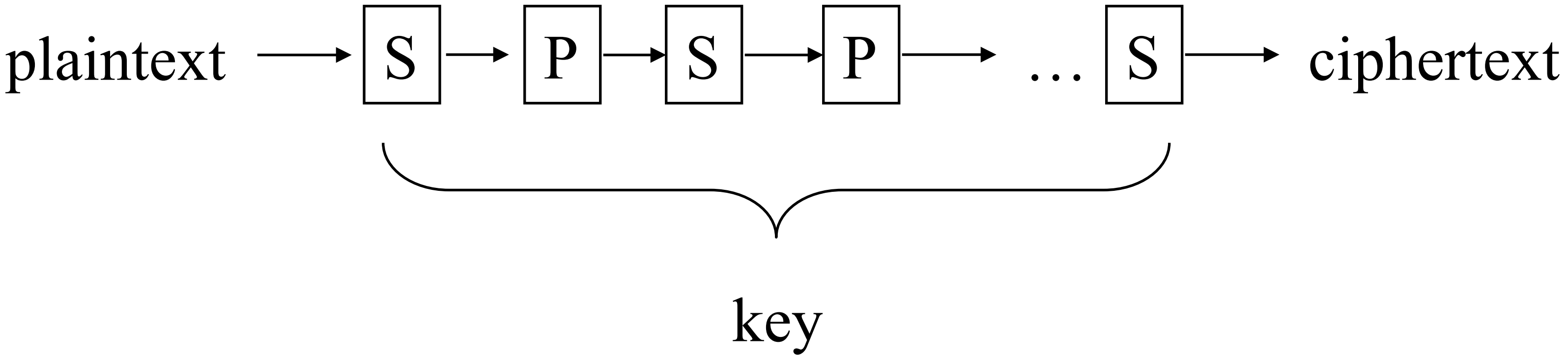
key ↑ (encryption) key ↑ (decryption)

key ← Same key → key

- 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



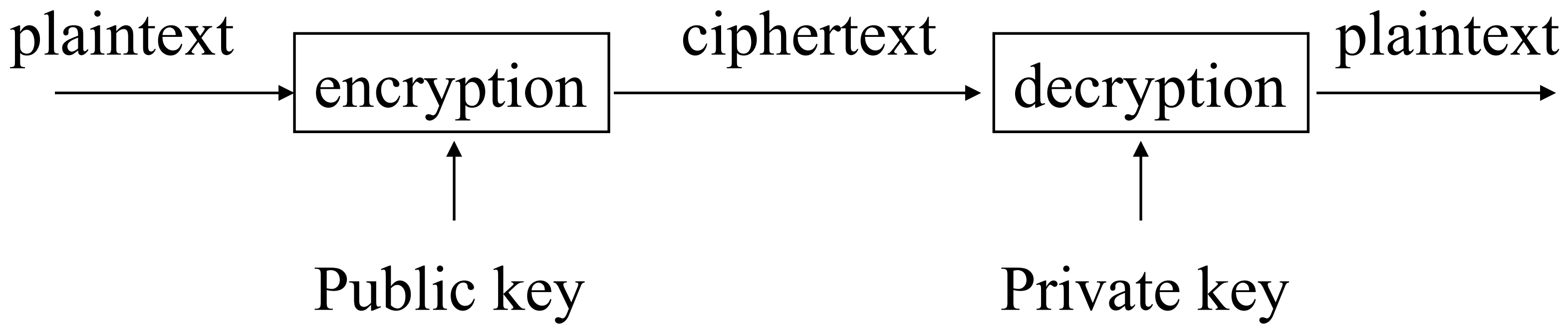
Secret Key Cryptography (Cont'd)

- 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?
- Secure Storage on insecure media
- 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 (PKC)

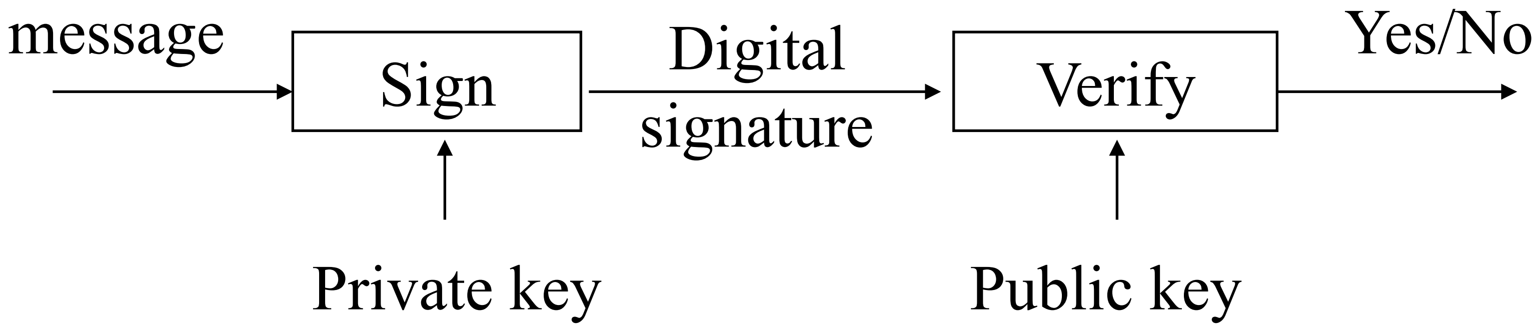

plaintext → encryption → ciphertext → decryption → plaintext

Public key ↑ encryption

Private key ↑ decryption

- 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.
  - The signature is created on a hash value of the message.

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 to store secrets, only need public keys.
  - Secret key cryptography: need to share secret key for every person to communicate with.

Applications of PKC (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

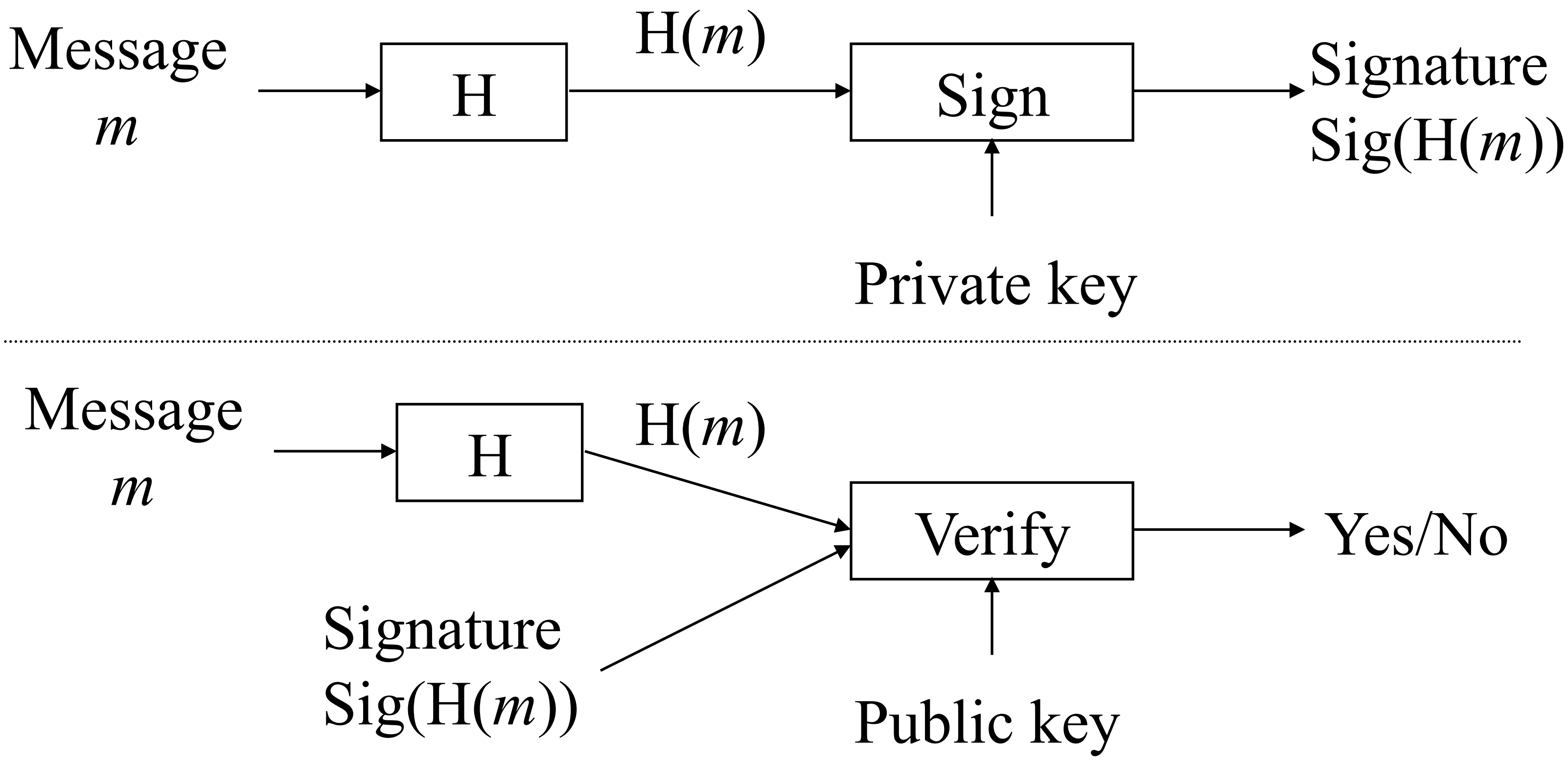
- Also known as
  - Message digests
  - One-way transformations
  - One-way functions
  - Hash functions
- Length of $H(m)$ much shorter then length of m
- Usually fixed lengths: 128 or 160 bits

Hash Algorithms (Cont'd)

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



Message m → H → $H(m)$ → Sign → Signature $Sig(H(m))$

Private key → Sign

Message m → H → $H(m)$ → Verify → Yes/No

Signature $Sig(H(m))$ → Verify

Public key → Verify

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