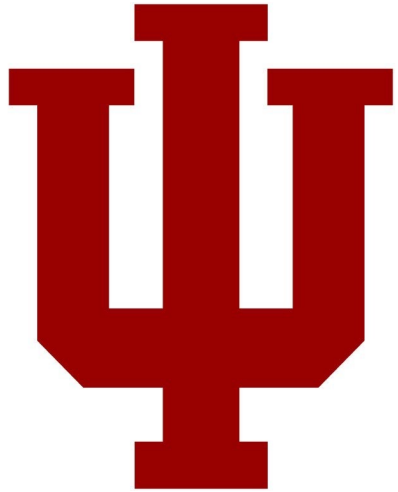
03 Cryptography I

Engr 399/599: Hardware Security

Andrew Lukefahr
Indiana University



Adapted from: Mark Tehranipoor of University of Florida

no assignments today

Switch to Xilinx Vivado for 1st project.

- not ready yet :'

- hopits Thurs.

- Office hours: M/W 4:30-6

Course Website

engr599.github.io

Write that down!

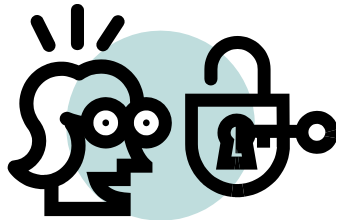
Some Basic Definitions

- **Intellectual property** represents the property of your mind or intellect - proprietary knowledge

- The four legally defined forms of IP
  - **Patents** When you register your invention with the government, you gain the legal right to exclude anyone else from manufacturing or marketing it
  - **Trademarks** A trademark is a name, phrase, sound or symbol used in association with services or products
  - **Copyrights** Copyright laws protect written or artistic expressions fixed in a tangible medium
  - **Trade secrets** A formula, pattern, device or compilation of data that grants the user an advantage over competitors

Some Basic Definitions (Cont'd)

- **Cryptography**:
  - crypto (secret) + graph (writing)
    - the science of locks and keys
  - The keys and locks are mathematical
  - Underlying every security mechanism, there is a "secret"…
  - We are going to talk some about the traditional crypto, but we will also show new forms of security based on other forms of HW-based secret



What Does Secure Mean?

- It has to do with an asset that has some value – think of what can be an asset!
- There is no static definition for “secure”
- Depends on what is that you are protecting your asset from
- Protection may be sophisticated and unsophisticated
- Typically, breach of one security makes the protection agent aware of its shortcoming

Typical Cycle in Securing a System

- Predict potential breaches and vulnerabilities
- Consider possible countermeasures, or controls
- Either actively pursue identifying a new breach, or wait for a breach to happen
- Identify the breach and work out a protected system again

Computer Security

- No matter how sophisticated the protection system is – simple breaches could break-in
- A computing system is a collection of hardware (HW), software (SW), storage media, data, and human interacting with them
- Security of SW, data, and communication
- HW security, is important and challenging
  - Manufactured ICs are obscure
  - HW is the platform running SW, storage and data
  - Tampering can be conducted at many levels
  - Easy to modify because of its physical nature

Definitions

- **Vulnerability**: Weakness in the secure system
- **Threat**: Set of circumstances that has the potential to cause loss or harm
- **Attack**: The act of a human exploiting the vulnerability in the system
- **Computer security aspects**
  - **Confidentiality**: the related assets are only accessed by authorized parties
  - **Integrity**: the asset is only modified by authorized parties
  - **Availability**: the asset is accessible to authorized parties at appropriate times

Hardware Vulnerabilities

- Physical Attacks
- Trojan Horses
- IP Piracy
- IC Piracy & Counterfeiting
- Backdoors
- Tampering
- Reverse Engineering

Adversaries

- **Individual, group or governments**
  - Pirating the IPs – illegal use of IPs
  - Inserting backdoors, or malicious circuitries
  - Implementing Trojan horses
  - Reverse engineering of ICs
  - Spying by exploiting IC vulnerabilities
- **System integrators**
  - Pirating the IPs
- **Fabrication facilities**
  - Pirating the IPs
  - Pirating the ICs
- **Counterfeiting parties**
  - Recycling, cloned, etc.

Hardware Controls for Secure Systems

- Hardware implementations of encryption
  - Encryption has to do with scrambling to hide
- Design locks or physical locks limiting the access
- Devices to verify the user identities
- Hiding signatures in the design files
- Intrusion detection
- Hardware boards limiting memory access
- Tamper resistant
- Policies and procedures
- More …

Secret

- **Underlying most security mechanisms or protocols is the notion of a "secret"**
  - Lock and keys
  - Passwords
  - Hidden signs and procedures
  - Physically hidden

Bank
Personal info
location

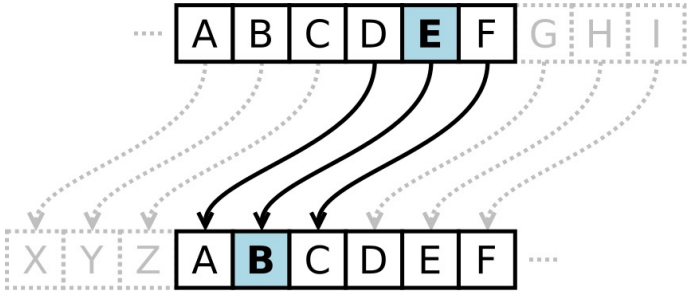
IP (designs)
addr
IPv4

Cryptography – History

- Has been around for 2000+ years
- In 513 B.C, Histiaeus of Miletus, shaved the slave's head, tattooed the message on it, let the hair grow

Cryptography – Pencil & Paper Era

- Caesar's cipher: shifting each letter of the alphabet by a fixed amount!
  - Easy to break




```
Plaintext: THE QUICK BROWN FOX JUMPS OVER THE LAZY DOG
Ciphertext: QEB NRFZH YOLTK CLU GRJMP LSBO QEB IXWV ALD
```

- Cryptoquote: simple substitution cipher, permutations of 26 letters
  - Using the dictionary and the frequencies, this is also easy to break

Caesar Cypher Example

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

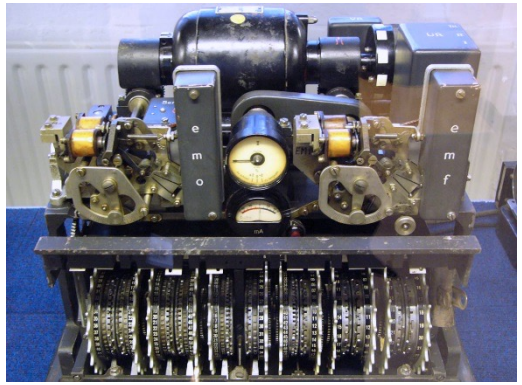
D E F G H I J K L M N O P Q R S T U V W X Y Z A B C

Cryptography – Mechanical Era

- Around 1900, people realized cryptography has math and stat roots
- German's started a project to create a mechanical device to encrypt messages
- Enigma machine → supposedly unbreakable
- A few polish mathematicians got a working copy
- The machine later sold to Britain, who hired 10,000 people to break the code!
- They did crack it! The German messages were transparent to enemies towards the end of war
  - **Estimated that it cut the war length by about a year**
- British kept it secret until the last working Enigma!

Cryptography – Mechanical Era

- Another German-invented code was Tunny (Lorenz cipher system)
- Using a pseudorandom number generator, a seed produced a key stream *ks*
- The key stream xor'd with plain text p to produce cipher c: $c=p \oplus ks$
- How was this code cracked by British cryptographers at Bletchley Park in Jan 1942?
- A lucky coincidence!



German rotor stream cipher machines used by the German Army during World War II

Summary

- Substitution ciphers
- Permutations
- Making good ciphers
- Data Encryption Standard (DES)
- Advanced Encryption Standard (AES)

Slides are courtesy of Leszek T. Lilien from WMich
http://www.cs.wmich.edu/~llilien/

Terminology and Background
Threats to Messages

- Interception
- Interruption
  - Blocking msgs
- Modification
- Fabrication

"A threat is blocked by control of a vulnerability"

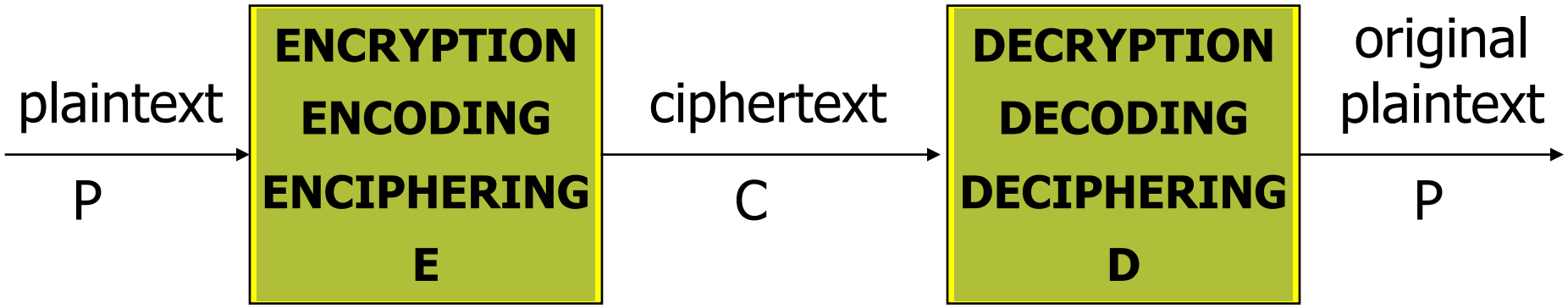
[Pfleeger & Pfleeger]

[cf. B. Endicott-Popovsky, U. Washington]

Basic Terminology & Notation

- **Cryptology:**
  - cryptography + cryptanalysis
- **Cryptography:**
  - art/science of keeping message secure
- **Cryptanalysis:**
  - art/science of breaking ciphertext
    - *Enigma* in world war II
      - Read the real story – not fabrications!

Basic Cryptographic Scheme



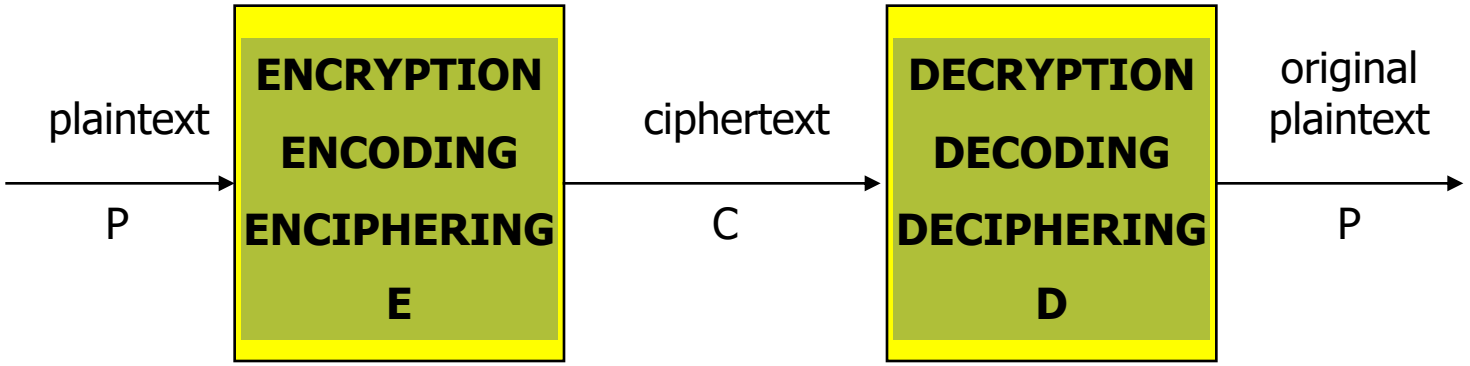
- $P = <p_1, p_2, \ldots, p_n>$ p_i = i-th char of P
  - P = "DO NOT TELL ANYBODY" p_1 ="D", p_2 = "O", etc.
  - By convention, cleartext in uppercase
- $C = <c_1, c_2, \ldots, c_n>$ c_i = i-th char of C
  - C = "ep opu ufmm bozcpez" c_1 ="e", c_2 ="p", etc.
  - By convention, ciphertext in lowercase

Benefits of Cryptography

- **Improvement not a Solution!**
  - Minimizes problems
  - Doesn't solve them
    - Remember: There is *no* solution!
  - Adds an envelope (encoding) to an open postcard (plaintext or cleartext)

[cf. D. Frincke, U. of Idaho]

Formal Notation



- C = E(P)
- P = D(C)

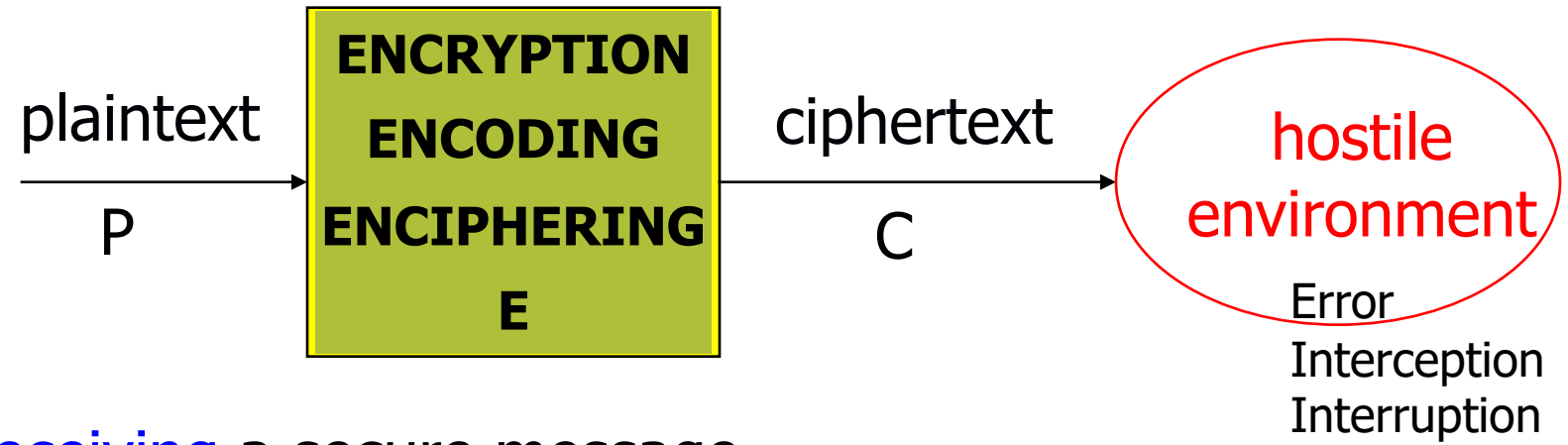
E – encryption rule/algorithm

D – decryption rule/algorithm

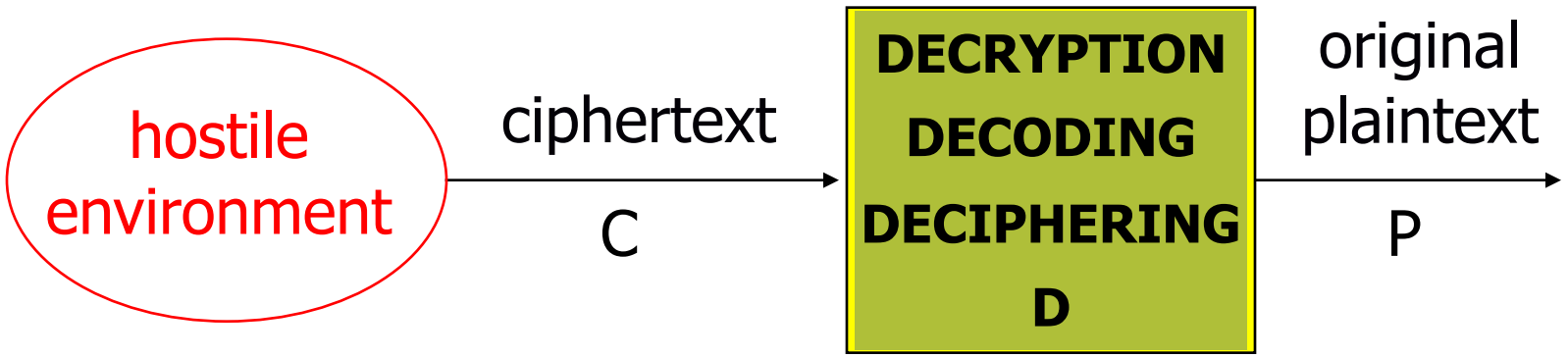
- We need a cryptosystem, where:
  - P = D(C)= D(E(P))
    - i.e., able to get the original message back

Cryptography in Practice

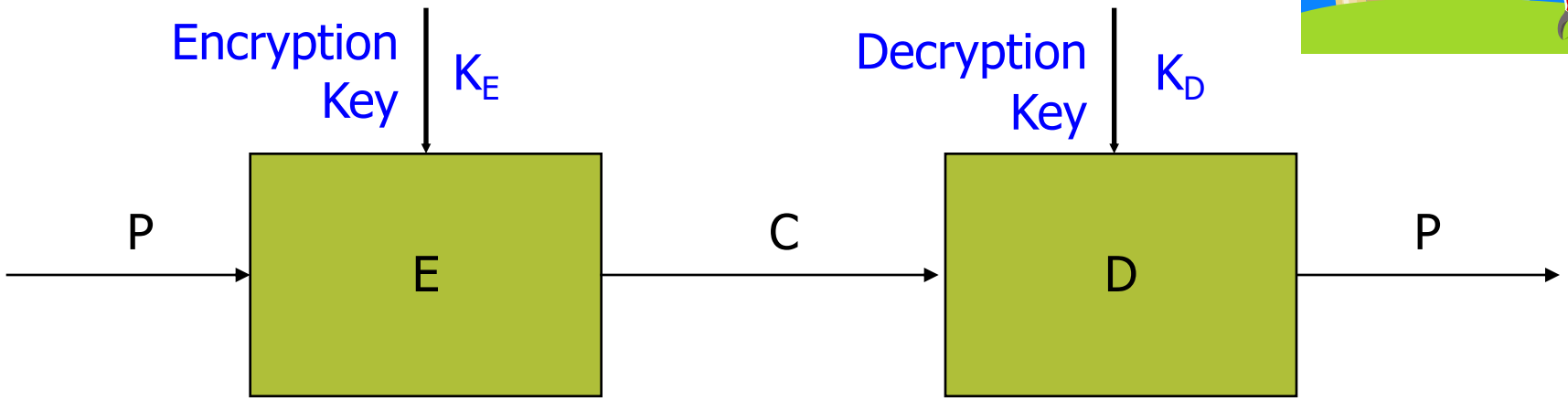
- Sending a secure message



- Receiving a secure message



Crypto System with Keys



- $C = E(K_E, P)$
  - E = *set* of encryption algorithms / K_E selects $E_i \in E$
- $P = D(K_D, C)$
  - D = *set* of decryption algorithms / K_D selects $D_j \in D$
- Crypto algorithms and keys are like door locks and keys
- We need: $P = D(K_D, E(K_E, P))$

Classification of Cryptosystems w.r.t. Keys

- Keyless cryptosystems exist (e.g., Caesar's cipher)
  - Less secure
- Symmetric cryptosystems: $K_E = K_D$
  - Classic
  - Encipher and decipher using the same key
    - Or one key is easily derived from other
- Asymmetric cryptosystems: $K_E \neq K_D$
  - Public key system
  - Encipher and decipher using different keys
    - Computationally infeasible to derive one from other

[cf. B. Endicott-Popovsky, U. Washington]

Cryptanalysis (1)

- **Cryptanalysts goals:**
  - Break a single msg
  - Recognize patterns in encrypted msgs, to be able to break the subsequent ones
  - Infer meaning w/o breaking encryption
    - Unusual volume of msgs between enemy troops may indicate a coming attack
    - Busiest node may be enemy headquarters
  - Deduce the key, to facilitate breaking subsequent msgs
  - Find vulnerabilities in implementation or environment of an encryption algorithm
  - Find a general weakness in an encryption algorithm

Cryptanalysis (2)

- **Information for cryptanalysts:**
  - Intercepted encrypted msgs
  - Known encryption algorithms
  - Intercepted plaintext
  - Data known or suspected to be ciphertext
  - Math or statistical tools and techniques
  - Properties of natural languages
    - Esp. adversary's natural language
      - To confuse the enemy, Americans used Navajo language in WW2
  - Propertiers of computer systems
- Role of ingenuity / luck
- There are *no* rules!!!

Breakable Encryption (1)

- **Breakable encryption**
  - *Theoretically*, it is possible to devise unbreakable cryptosystems
  - *Practical* cryptosystems almost always are breakable, given adequate time and computing power
  - The trick is to make breaking a cryptosystem hard enough for the intruder

[cf. J. Leiwo, VU, NL]

Breakable Encryption (2)

- Example: Breakability of an encryption algorithm

  Msg with just 25 characters
  - 26^{25} possible decryptions ~ 10^{35} decryptions
  - Only one is the right one
  - Brute force approach to find the right one:
    - At 10^{10} (10 bln) decryption/sec => 10^{35} / 10^{10} = 10^{16} sec = 10 bln yrs !
    - Infeasible with current technology
- Be smarter – use ingenuity
  - Could reduce 26^{25} to, say, 10^{15} decryptions to check

    At 10^{10} decr./sec => 10^{15} / 10^{10} = 10^{5} sec = ~ 1 day

Requirements for Crypto Protocols

- Messages should get to destination
- Only the recipient should get it
- Only the recipient should see it
- Proof of the sender's identity
- Message shouldn't be corrupted in transit
- Message should be sent/received once

[cf. D. Frincke, U. of Idaho]

- Proofs that message was sent/received (non-repudiation)

Representing Characters

- Letters (uppercase only) represented by numbers 0-25 (modulo 26).

```
A  B  C  D  ...   X   Y   Z
0  1  2  3  ... 23  24  25
```

- Operations on letters:

```
A + 2 = C
X + 4 = B
...
```

(circular!)

Basic Types of Ciphers

- Substitution ciphers
  - Letters of P replaced with other letters by E
- Transposition (permutation) ciphers
  - *Order* of letters in P rearranged by E
- Product ciphers
  - E "=" E_1 "+" E_2 "+" ... "+" E_n
    - Combine two or more ciphers to enhance the security of the cryptosystem

Substitution Ciphers

- **Substitution Ciphers:**
  - **Letters of P replaced with other letters by E**

The Caesar Cipher (1)

- $c_i = E(p_i) = p_i + 3 \bmod 26$ (*26* letters in the English alphabet)

  Change each letter to the third letter following it (circularly)

  A → D, B → E, … X → A, Y → B, Z → C

- Can represent as a permutation π: $\pi(i) = i+3 \bmod 26$

  $\pi(0)=3$, $\pi(1)=4$, …,

  $\pi(23)=26 \bmod 26=0$, $\pi(24)=1$, $\pi(25)=2$

- Key = 3, or key = 'D' (because D represents 3)

The Caesar Cipher (2)

- Example [cf. B. Endicott-Popovsky]
  - P (plaintext): HELLO WORLD
  - C (ciphertext): khoor zruog

- Caesar Cipher is a monoalphabetic substitution cipher (= simple substitution cipher)
  One key is used
  One letter substitutes the letter in P

Attacking a Substitution Cipher

- Exhaustive search
  - If the key space is small enough, try all possible keys until you find the right one
  - Cæsar cipher has 26 possible keys
    from A to Z OR: from 0 to 25
- Statistical analysis (attack)
  - Compare to so called 1-gram (unigram) model of English
    - 1-gram: It shows frequency of (single) characters in English
  - The longer the C, the more effective statistical analysis would be

[cf. Barbara Endicott-Popovsky, U. Washington]

1-grams (Unigrams) for English

a	0.080	h	0.060	n	0.070	t	0.090
b	0.015	i	0.065	o	0.080	u	0.030
c	0.030	j	0.005	p	0.020	v	0.010
d	0.040	k	0.005	q	0.002	w	0.015
e	0.130	l	0.035	r	0.065	x	0.005
f	0.020	m	0.030	s	0.060	y	0.020
g	0.015					z	0.002

[cf. Barbara Endicott-Popovsky, U. Washington]

Statistical Attack – Step 1

- Compute frequency f(c) of each letter c in ciphertext
- Example: c = 'khoor zruog'
  - 10 characters: 3 * 'o', 2 * 'r', 1 * {k, h, z, u, g}
  - f(c):

    f(g)=0.1 f(h)=0.1 f(k)=0.1 f(o)=0.3 f(r)= 0.2

    f(u)=0.1 f(z)=0.1 $f(c_i) = 0$ for any other c_i
- Apply 1-gram model of English
  - Frequency of (single) characters in English
  - 1-grams on previous slide

[cf. Barbara Endicott-Popovsky, U. Washington]

Statistical Analysis – Step 2

- phi $\varphi(i)$ - correlation of frequency of letters *in ciphertext* with frequency of corresponding letters *in English* —for key i
- For key i: $\varphi(i) = \Sigma_{0 \le c \le 25} f(c) * p(c - i)$
  - *c* representation of character (a-0, ..., z-25)
  - f(c) is frequency of letter c in ciphertext C
  - *p*(*x*) is frequency of character *x* in English
  - Intuition: sum of probabilities for words in P, if i were the key

c is a letter in ciphertext thus c-i is the letter in plaintext.

- Example: C = 'khoor zruog' (P = 'HELLO WORLD')

f(c): f(g)=0.1, f(h)=0.1, f(k)=0.1, f(o)=0.3, f(r)=0.2, f(u)=0.1, f(z)=0.1

c: g - 6, h - 7, k - 10, o - 14, r - 17, u - 20, z - 25

$$\varphi(i) = 0.1p(6 - i) + 0.1p(7 - i) + 0.1p(10 - i) + 0.3p(14 - i) + 0.2p(17 - i) + 0.1p(20 - i) + 0.1p(25 - i)$$

[cf. Barbara Endicott-Popovsky, U. Washington]

Statistical Attack – Step 2a (Calculations)

- Correlation $\varphi(i)$ for $0 \leq i \leq 25$

i	$\varphi(i)$	*i*	$\varphi(i)$	*i*	$\varphi(i)$	*i*	$\varphi(i)$
0	0.0482	7	0.0442	13	0.0520	19	0.0315
1	0.0364	8	0.0202	14	0.0535	20	0.0302
2	0.0410	9	0.0267	15	0.0226	21	0.0517
3	0.0575	10	0.0635	16	0.0322	22	0.0380
4	0.0252	11	0.0262	17	0.0392	23	0.0370
5	0.0190	12	0.0325	18	0.0299	24	0.0316
6	0.0660					25	0.0430

[cf. Barbara Endicott-Popovsky, U. Washington]

Statistical Attack – Step 3 (The Result)

- Most probable keys (largest $\varphi(i)$ values):
  - i = 6, $\varphi(i)$ = 0.0660
    - plaintext EBIIL TLOLA
  - i = 10, $\varphi(i)$ = 0.0635
    - plaintext AXEEH PHKEW
  - i = 3, $\varphi(i)$ = 0.0575
    - plaintext HELLO WORLD
  - i = 14, $\varphi(i)$ = 0.0535
    - plaintext WTAAD LDGAS
- Only English phrase is for *i* = 3
  - That's the key (3 or 'D') – code broken

[cf. Barbara Endicott-Popovsky, U. Washington]

Caesar's Problem

- Conclusion: Key is too short
  - 1-char key – monoalphabetic substitution
    - Can be found by exhaustive search
    - Statistical frequencies not concealed well by short key
      - They look too much like 'regular' English letters

- Solution: Make the key longer
  - n-char key ($n \geq 2$) – polyalphabetic substitution
    - Makes exhaustive search much more difficult
    - Statistical frequencies concealed much better
      - Makes cryptanalysis harder

[cf. Barbara Endicott-Popovsky, U. Washington]

Other Substitution Ciphers

n-char key:

- Polyalphabetic substitution ciphers
- Vigenere Tableaux cipher

Polyalphabetic Substitution - Examples

- Flatten (difuse) *somewhat* the frequency distribution of letters by combining high and low distributions

- Example – 2-key substitution:

	A	B	C	D	E	F	G	H	I	J	K	L	M
Key1:	a	d	g	j	m	p	s	v	y	b	e	h	k
Key2:	n	s	x	c	h	m	r	w	b	g	l	q	v

	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Key1:	n	q	t	w	z	c	f	i	l	o	r	u	x
Key2:	a	f	k	p	u	z	e	j	o	t	y	d	i

- **Question**:

  How Key1 and Key2 were defined?

[cf. J. Leiwo, VU, NL]

Polyalphabetic Substitution - Examples

- ...

- Example:

	A	B	C	D	E	F	G	H	I	J	K	L	M
Key1:	a	d	g	j	m	p	s	v	y	b	e	h	k
Key2:	n	s	x	c	h	m	r	w	b	g	l	q	v

	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Key1:	n	q	t	w	z	c	f	i	l	o	r	u	x
Key2:	a	f	k	p	u	z	e	j	o	t	y	d	i

  - Answer:

    Key1 – start with ‘a’, skip 2, take next,
    skip 2, take next letter, ... (circular)

    Key2 - start with ‘n’ (2nd half of alphabet), skip 4,
    take next, skip 4, take next, ... (circular)

[cf. J. Leiwo, VU, NL]

Polyalphabetic Substitution - Examples

– Example:

	A	B	C	D	E	F	G	H	I	J	K	L	M
Key1:	a	d	g	j	m	p	s	v	y	b	e	h	k
Key2:	n	s	x	c	h	m	r	w	b	g	l	q	v

	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Key1:	n	q	t	w	z	c	f	i	l	o	r	u	x
Key2:	a	f	k	p	u	z	e	j	o	t	y	d	i

– **Plaintext: TOUGH STUFF**

– **Ciphertext: ffirv zfjpm**

use n (=2) keys in turn for consecutive P chars in P

- Note:
  - Different chars mapped into the same one: **T, O → f**
  - Same char mapped into different ones: **F → p, m**
  - '**f**' most frequent in C (0.30); in English: f(**f**) = 0.02 << f(**e**) = 0.13

[cf. J. Leiwo, VU, NL]

Vigenere Tableaux (1)

Note: Row A – shift 0 (a->a)
Row B – shift 1 (a->b)
Row C – shift 2 (a->c)
...
Row Z – shift 25 (a->z)

[cf. J. Leiwo, VU, NL]

	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	p
A	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	0
B	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	a	1
C	c	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	2
D	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	3
E	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	d	4
F	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	5
G	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	6
H	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	7
I	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	8
J	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	9
K	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	10
L	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	11
M	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	12
N	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	13
O	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	14
P	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	15
Q	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	16
R	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	17
S	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	18
T	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	19
U	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	20
V	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	21
W	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	22
X	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	23
Y	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	24
Z	z	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	25

Vigenère Tableaux (2)

- Example

  Key:

  EXODUS

  Plaintext P:

  YELLOW SUBMARINE FROM YELLOW RIVER

  Extended keyword (re-applied to mimic words in P):

  YELLOW SUBMARINE FROM YELLOW RIVER

  EXODUS EXODUSEXO DUSE XODUSE XODUS

  Ciphertext:

  cbxoio wlppujmks ilgq vsofhb owyyj

[cf. J. Leiwo, VU, NL]

Vigenère Tableaux (3)

- Example

  …

  Extended keyword (re-applied to mimic words in P):

  `YELLOW SUBMARINE FROM YELLOW RIVER`

  `EXODUS EXODUSEXO DUSE XODUSE XODUS`

  Ciphertext:

  `cbzoio wlppujmks ilgq vsofhb owyyj`

- Answer:

  c from P indexes row

  c from extended key indexes column

  e.g.: row Y and column e → ‘c’

  row E and column x → ‘b’

  row L and column o → ‘z’

  …

[cf. J. Leiwo, VU, NL]

Transposition Ciphers (1)

- Rearrange letters in plaintext to produce ciphertext
- Example 1a and 1b: Columnar transposition
  - Plaintext: **HELLO WORLD**
  - Transposition onto: (a) 3 columns:

    HEL
    LOW
    ORL
    DXX **XX** - padding

    (b) onto 2 columns:

    HE
    LL
    OW
    OR
    LD

  - Ciphertext (read column-by column):

    (a) **hlodeorxlwlx**

    (b) **hloolelwrd**

  - What is the key?
    - Number of columns: (a) key = 3 and (b) key = 2

Transposition Ciphers (2)

- Example 2: Rail-Fence Cipher
  - Plaintext: **HELLO WORLD**
  - Transposition into 2 rows (rails) column-by-column:

    HLOOL

    ELWRD
  - Ciphertext: **hloolelwrd** (Does it look familiar?)

    [cf. Barbara Endicott-Popovsky, U. Washington]
  - What is the key?
    - Number of rails key = 2

Product Ciphers

- A.k.a. combination ciphers
- Built of multiple blocks, each is:
  - Substitution

or:

  - Transposition
- Example: two-block product cipher
  - $E_2(E_1(P, K_{E1}), K_{E2})$
- Product cipher might *not* necessarily be stronger than its individual components used separately!
  - Might not be even as strong as individual components

Criteria for "Good" Ciphers

- "Good" depends on intended application
  - Substitution
    - C hides chars of P
    - If > 1 key, C dissipates high frequency chars
  - Transposition
    - C scrambles text => hides n-grams for n > 1
  - Product ciphers
    - Can do all of the above
  - What is more important for your app?
    What facilities available to sender/receiver?
    - E.g., no supercomputer support on the battlefield

Criteria for "Good" Ciphers

stop here!

- **Commercial Principles of Sound Encryption Systems**
  1. Sound mathematics
     - Proven vs. not broken so far
  2. Verified by expert analysis
     - Including outside experts
  3. Stood the test of time
     - Long-term success is not a guarantee
       - Still. Flows in many E's discovered soon after their release

- Examples of popular commercial encryption:
  - DES / RSA / AES

DES = Data Encryption Standard
RSA = Rivest-Shamir-Adelman
AES = Advanced Encryption Standard (rel. new)

Elliptic Curve Crypto

[cf. A. Striegel]

Stream and Block Ciphers (1)

a. Stream ciphers

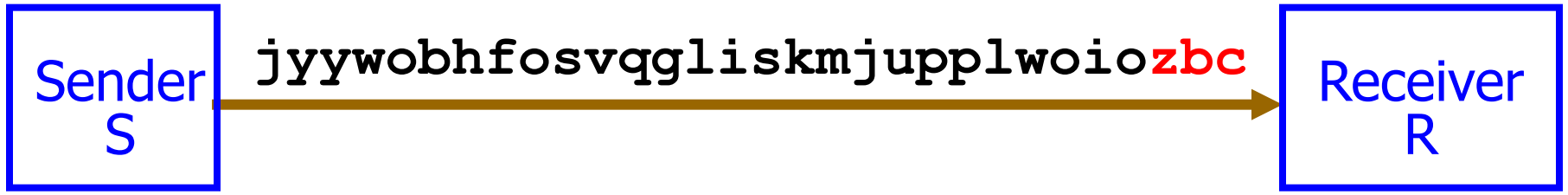
b. Problems with stream ciphers

c. Block ciphers

d. Pros / cons for stream and block ciphers

Stream Ciphers (1)

- Stream cipher: 1 char from P → 1 char for C
  - Example: polyalphabetic cipher
    - P and K (repeated '**EXODUS**'):
      YELLOWSUBMARINEFROMYELLOWRIVER
      EXODUSEXODUSEXODUSEXODUSEXODUS
    - Encryption (char after char, using Vigenère Tableaux):
      (1) E(**Y**, **E**) → **c** (2) E(**E**, **X**) → **b** (3) E(**L**, **O**) → **z** . . .
    - C: **cbzoiowlppujmksilgqvsofhbowyyj**
    - C as sent (in the right-to-left order):



Stream Ciphers (2)

– Example: polyalphabetic cipher - cont.

- C as received (in the right-to-left order):

- C and K for decryption:

  cbzoiowlppujmksilgqvsofhbowyyj
  EXODUSEXODUSEXODUSEXODUSEXODUS

- Decryption:
  (1) D(**c**, **E**) → **Y** (2) D(**b**, **X**) → **E** (3) D(**z**, **O**) → **L** . . .

- Decrypted P:

  YEL. . .

Q: Do you know how D uses Vigenère Tableaux?

A: Finds c under column e ➔ Y

Problems with Stream Ciphers (1)

- Problems with stream ciphers
  - Dropping a char from key K results in wrong decryption
  - Example:
    - P and K (repeated '**EXODUS**') with a char in K missing:

      YELLOWSUBMARINEFROMYELLOWRIVER
      EODUSEXODUSEXODUSEXODUSEXODUSE

      missing X in K ! (no errors in repeated K later)

    - Encryption (using VT):

      1) E(**Y**,**E**) → **c**
      2) E(**E**,**O**) → **s**
      3) E(**L**,**D**) → **o**

      ...

    - Ciphertext: **cso...**

      C in the order as sent (right-to-left):

      ...osc

Problems with Stream Ciphers (2)

- C as received (in the right-to-left order):

  ...osc

- C and correct K ('**EXODUS**') for decryption:

  cso...

  EXO...

- Decryption (using VT, applying correct key):

  1) D(**c**, **E**) → **Y**

  2) D(**s**, **X**) → **V**

  3) D(**o**, **O**) → **A**

  ...

- Decrypted P:

  YVA... - Wrong!

  – We know it's wrong, Receiver might not know it *yet*!

What if message is corrupted in a noisy area?

Problems with Stream Ciphers (3)

- The problem might be recoverable
  - Example:

    If R had more characters decoded, R might be able to detect that S dropped a key char, and R could recover
    - E.g., suppose that R decoded:

      YELLOW SUBMAZGTR
      - R could guess, that the 2nd word should really be:

        SUBMARINE
      - => R would know that S dropped a char from K after sending "**SUBMA**"
      - => R could go back 4 chars, drop a char from K ("recalibrate K with C"), and get "resynchronized" with S

Block Ciphers (1)

- We can do better than using recovery for stream ciphers
  - Solution: use block ciphers

- Block cipher:
  1 *block* of chars from P → 1 *block* of chars for C
  - Example of block cipher: columnar transposition
  - Block size = "o(message length)" (informally)

Block Ciphers (2)

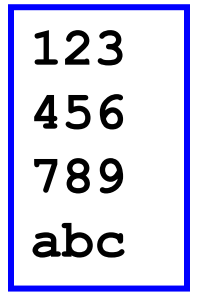
- Why block size = "o(message length)" ?
  - Because R must wait for "almost" the entire C before R can decode some characters near beginning of P
  - E.g., for P = '**HELLO WORLD**', block size is "o(10)"
  - Suppose that Key = 3 (3 columns):

HEL
LOW
ORL
DXX

  - C as sent (in the right-to-left order):

Block Ciphers (3)

- C as received (in the right-to-left order): **xlwlxroedolh**
- R knows: K = 3, block size = 12 (=> 4 rows)



a=10
b=11
c=12

=> R knows that characters wil be sent in the order:
1st-4th-7th-10th--2nd-5th-8th-11th--3rd-6th-9th-12th

- R must wait for at least:
  - 1 char of C to decode 1st char of P ('**h**')
  - 5 chars of C to decode 2nd char of P ('**he**')
  - 9 chars of C to decode 3rd, 4th, and 5th chars of P ('**hello**')
  - 10 chars of C to decode 6th, 7th, and 8th chars of P ('**hello wor**')
  - etc.

Block Ciphers (4)

- *Informally*, we might call ciphers like the above example columnar transposition cipher "weak-block" ciphers
  - R can get some (even most) but not all chars of P before entire C is received
    - R can get one char of P immediately
      - » the 1st-after 1 of C (delay of 1 - 1 = 0)
    - R can get some chars of P with "small" delay
      - » e.g., 2nd-after 5 of C (delay of 5 - 2 = 3)
    - R can get some chars of P with "large" delay
      - » e.g., 3rd-after 9 of C (delay of 9 – 3 = 6)
- There are block ciphers when R cannot even start decoding C before receiving the entire C
  - *Informally*, we might call them "strong-block" ciphers

Pros / Cons for Stream and Block Ciphers (1)

- Pros / cons for stream ciphers
  - + Low delay for decoding individual symbols
    - Can decode as soon as received
  - + Low error propagation
    - Error in $E(c_1)$ does not affect $E(c_2)$
  - - Low diffusion
    - Each char separately encoded => carries over its frequency info
  - - Susceptibility to malicious insertion / modification
    - Adversary can fabricate a new msg from pieces of broken msgs, even if he doesn't know E (just broke a few msgs)

Pros / Cons for Stream and Block Ciphers (2)

- Pros / cons for block ciphers
  - + High diffusion
    - Frequency of a *char* from P diffused over (a few chars of) a *block* of C
  - + Immune to insertion
    - Impossible to insert a char into a block without easy detection (block size would change)
    - Impossible to modify a char in a block without easy detection (if checksums are used)

Pros / Cons for Stream and Block Ciphers (3)

- Pros / cons for block ciphers — Part 2
  - - High delay for decoding individual chars
    - See example for '**hello worldxx**' above
      - For some E can't decode even the 1st char before whole k chars of a block are received
  - - High error propagation
    - It affects the block, not just a single char

Cryptanalysis (1)

- What cryptanalysts do when confronted with unknown?

  Four possible situations w.r.t. available info:

  1) C available
  2) Full P available
  3) Partial P available
  4) E available (or D available)

- (1) – (4) suggest 5 different approaches

Cryptanalysis (2)

- Cryptanalyst approaches
  1) Ciphertext-only attack
     - We have shown examples for such attacks
       - E.g., for Caesar's cipher, columnar transposition cipher
  2) Known plaintext attack
     - Analyst have C and P
       - Needs to deduce E such that C=E(P), then finds D
  3) Probable plaintext attack
     - Partial decryption provides partial match to C
       - This provides more clues

Cryptanalysis (3)

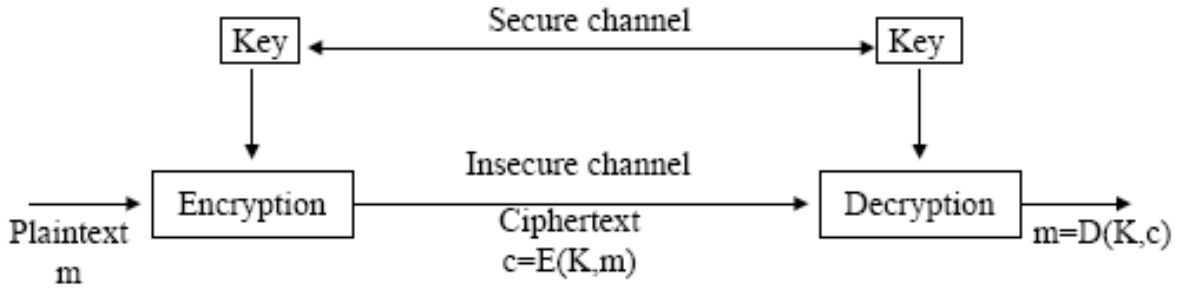
- Cryptanalyst approaches – cont.

4) Chosen plaintext attack
   - Analyst able to fabricate encrypted msgs
     - Then observe effects of msgs on adversary's actions
       - » This provides further hints

5) Chosen ciphertext attack
   - Analyst has both E and C
   - Run E for many candidate plaintexts to find P for which E(P) = C
     - Purpose: to find K_E

Symmetric and Asymmetric Cryptosystems (1)

- Symmetric encryption = secret key encryption
  - $K_E = K_D$ — called a secret key or a private key
  - Only sender S and receiver R know the key



[cf. J. Leiwo]

  - As long as the key remains secret, it also provides authentication (= proof of sender's identity)

Symmetric and Asymmetric Cryptosystems (3)

- Asymmetric encryption = public key encryption (PKE)
  - $K_E \neq K_D$ — public and private keys
- PKE systems eliminate symmetric encryption problems
  - Need no secure key distribution channel
    - => easy key distribution

Symmetric and Asymmetric Cryptosystems (4)

- One PKE approach:
  - R keeps her private key K_D
  - R can distribute the correspoding public key K_E to anybody who wants to send encrypted msgs to her
    - No need for secure channel to send K_E
    - Can even post the key on an open Web site — it is public!
  - Only private K_D can decode msgs encoded with public K_E!
    - Anybody (K_E is public) can encode
    - Only owner of K_D can decode

DES (Data Encryption Standard)

Background and History of DES (1)

- Early 1970's - NBS (Nat'l Bureau of Standards) recognized general public's need for a secure crypto system

  NBS – part of US gov't / Now: NIST – Nat'l Inst. of Stand's & Technology

  - "Encryption for the masses" [A. Striegel]
  - Existing US gov't crypto systems were not meant to be made public
    - E.g. DoD, State Dept.
  - Problems with proliferation of commercial encryption devices
    - Incompatible
    - Not extensively tested by independent body

Background and History of DES (2)

- 1972 - NBS calls for proposals for a *public* crypto system
  - Criteria:
    - Highly secure / easy to understand / publishable / available to all / adaptable to diverse app's / economical / efficient to use / able to be validated / exportable
    - In truth: Not *too* strong (for NSA, etc.)
- 1974 – IBM proposed its Lucifer
  - DES *based* on it
  - Tested by NSA (Nat'l Security Agency) and the general public
- Nov. 1976 – DES adopted as US standard for *sensitive but unclassified* data / communication
  - Later adopted by ISO (Int'l Standards Organization)
  - Official name: DEA - Data Encryption Algorithm / DEA-1 abroad

Overview of DES

- DES - a block cipher
  - a product cipher
  - 16 rounds (iterations) on the input bits (of P)
    - substitutions (for confusion) and permutations (for diffusion)
  - Each round with a *round key*
    - Generated from the user-supplied key
- Easy to implement in S/W or H/W

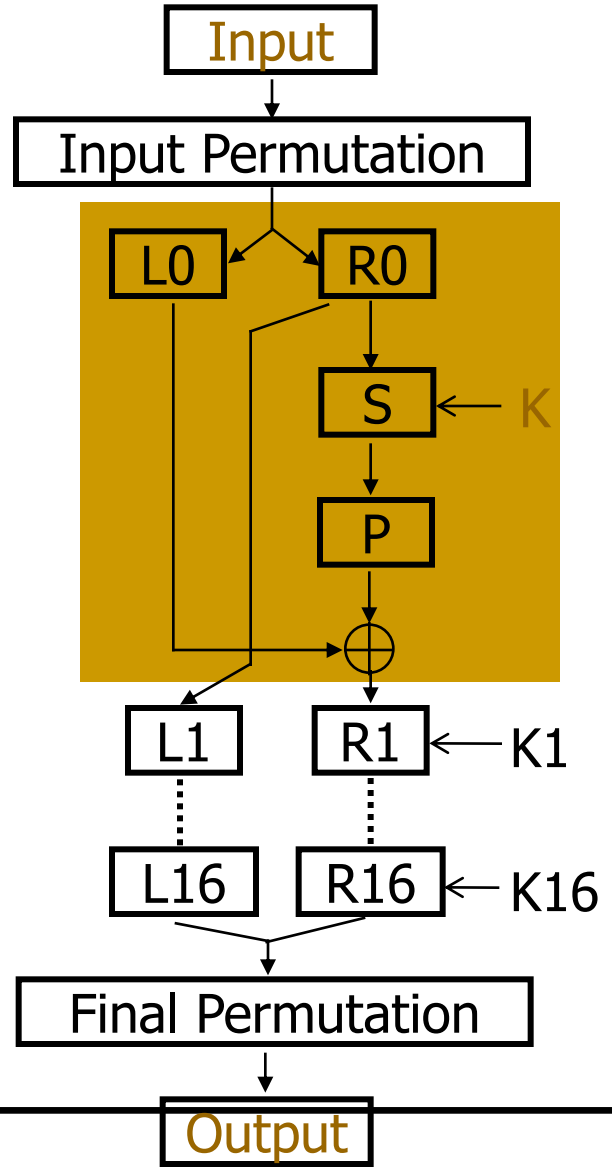
- There are 72,000,000,000,000,000 (72 quadrillion) or more possible encryption keys that can be used.
- For each given message, the key can be chosen at random from among this enormous number of keys.

Basic Structure

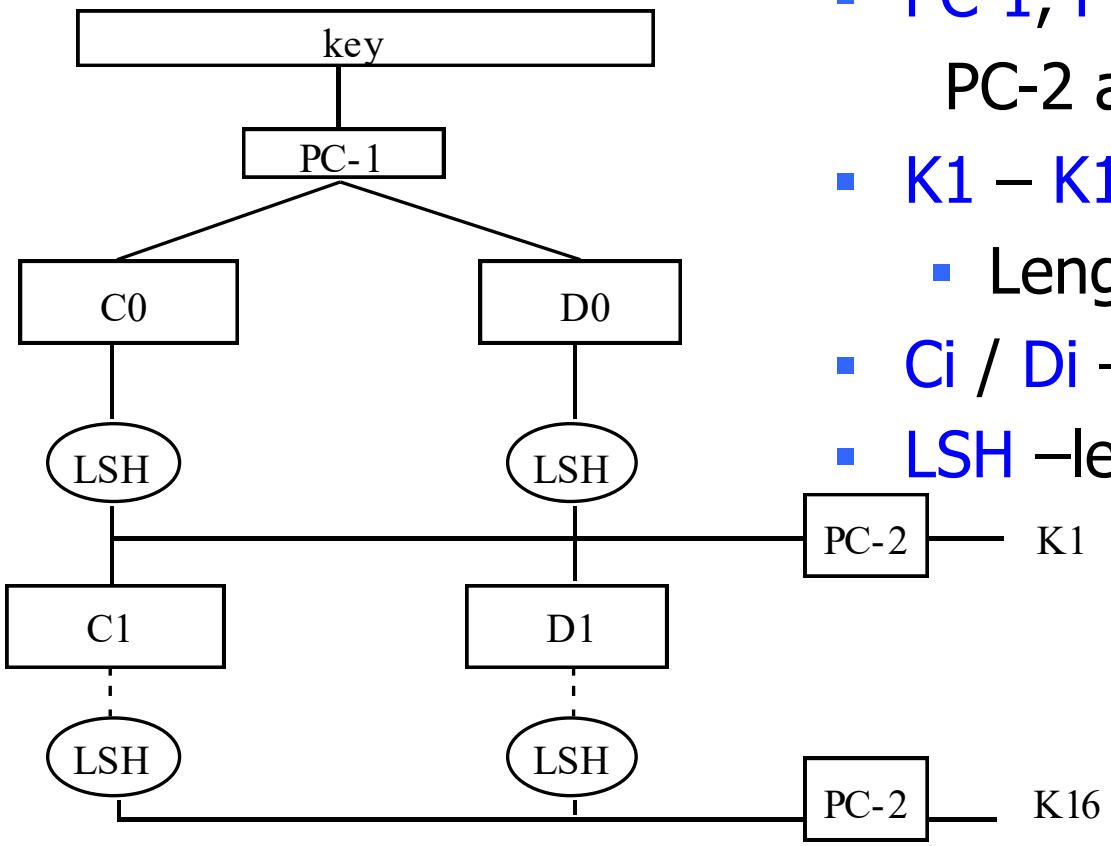
[Fig. – cf. J. Leiwo]

- Input: 64 bits (a block)
- Li/Ri– left/right half of the input block for iteration i (32 bits) – subject to substitution S and permutation P
- K - user-supplied key
- Ki - round key:
  - 56 bits used +8 unused

    (unused for E but often used for error checking)
- Output: 64 bits (a block)
- Note: Ri becomes L(i+1)
- All basic op's are simple logical ops
  - Left shift / XOR



Generation of Round Keys



- key – user-supplied key (input)
- PC-1, PC-2 – permutation tables
  PC-2 also extracts 48 of 56 bits
- K1 – K16 – round keys (outputs)
  - Length(Ki) = 48
- Ci / Di – confusion / diffusion (?)
- LSH –left shift (rotation) tables

[Fig: cf. Barbara Endicott-Popovsky, U. Washington]

Problems with DES

- Diffie, Hellman 1977 prediction: "In a few years, technology would allow DES to be broken in days."
- Key length is fixed (= 56)
  - 2^{56} keys ~ 10^{15} keys
  - "Becoming" too short for faster computers
    - 1997: 3,500 machines – 4 months
    - 1998: special "DES cracker" h/w – 4 days
- Design decisions not public
  - Suspected of having backdoors
    - Speculation: To facilitate government access?

Double and Triple DES

- Double DES:
  - Use double DES encryption

    C = E(k2, E(k1, P))
  - Expected to multiply difficulty of breaking the encryption
    - Not true!
      - In general, 2 encryptions are not better than one

        [Merkle, Hellman, 1981]
      - Only doubles the attacker's work

Double and Triple DES (2)

- Triple DES:
  - Is it C = E(k3, E(k2, E(k1, P)) ?
  - Not soooo simple!

Double and Triple DES (3)

- Triple DES: *Is it C=E(k3, E(k2, E(k1, P))?*
  - Tricks used:

    D not E in the 2nd step, k1 used twice (in steps 1 & 3)
  - It is:

    $$C = E(k1, D(k2, E(k1, P)))$$

    and

    $$P = D(k1, E(k2, D(k1, C)))$$
  - Doubles the effective key length
    - 112-bit key is quite strong
      - Even for today's computers
      - For all feasible known attacks

Security of DES

- So, is DES insecure?
- No, not yet
  - 1997 attack required a lot of cooperation
  - The 1998 special-purpose machine is still very expensive
  - Triple DES still beyond the reach of these 2 attacks
- But ...
  - In 1995, NIST (formerly NBS) began search for new strong encryption standard

The AES Contest (1)

- 1997 – NIST calls for proposals NIST (Nat'l Institute of Standards and Technology)
  - Criteria:
    - Unclassifed code
    - Publicly disclosed
    - Royalty-free worldwide
    - Symmetric block cipher for 128-bit blocks
    - Usable with keys of 128, 192, and 256 bits
- 1998 – 15 algorithms selected

The AES Contest (2)

- 1999 – 5 finalists [cf. J. Leiwo]
  - MARS by IBM
  - RC6 by RSA Laboratories
  - Rijndael (RINE-dahl) by Joan Daemen and Vincent Rijmen
  - Serpent by Ross Anderson, Eli Biham and Lars Knudsen
  - Twofish by Bruce Schneier, John Kelsey, Doug Whiting, Dawid Wagner, Chris Hall and Niels Ferguson
- Evaluation of finalists
  - Public and private scrutiny
  - Key evaluation areas:

    security / cost or efficiency of operation /

    ease of software implementation

The AES Contest (3)

- 2001- … and the winner is …

  Rijndael (RINE-dahl)

  Authors: Vincent Rijmen + Joan Daemen (Dutchmen)

- Adopted by US gov't as

  Federal Info Processing Standard 197 (FIPS 197)

Overview of Rijndael/AES

- Similar to DES – cyclic type of approach
  - 128-bit blocks of P
  - # of iterations based on key length
    - 128-bit key => 9 "rounds" (called rounds, not cycles)
    - 192-bit key => 11 rounds
    - 256-bit key => 13 rounds
- Basic ops for a round:
  - Substitution – byte level (confusion)
  - Shift row (transposition) – depends on key length (diff.)
  - Mix columns – LSH and XOR (confusion +diffusion)
  - Add subkey – XOR used (confusion)

Strengths of AES

- Extensive cryptanalysis by US gov't and independent experts
- Dutch inventors have no ties to NSA or other US gov't bodies (less suspicion of trapdoor)
- Solid math basis
  - Despite seemingly simple steps within rounds

Comparison of DES & AES (1)

	DES	AES
Date	1976	1999
Block size [bits]	64	128
Key length [bits]	56 (effect.)	128, 192, 256, or more
Encryption Primitives	substitution, permutation	substitution, shift, bit mixing
Cryptographic Primitives	confusion, diffusion	confusion, diffusion
Design	open	open
Design Rationale	closed	open
Selection process	secret	secret, but accepted public comments
Source	IBM, enhan-ced by NSA	independent Dutch cryptographers

Comparison of DES & AES (2)

- Weaknesses in AES?
  - 20+ yrs of experience with DES eliminated fears of its weakness (intentional or not)
    - Might be naïve…
  - Experts pored over AES for 2-year review period

Comparison of DES & AES (3)

- Longevity of AES?
  - DES is nearly 40 yrs old (1976)
    - DES-encrypted message can be cracked in days
  - Longevity of AES more difficult to answer
    - Can extend key length to > 256 bits (DES: 56)
      - 2 * key length => 4 * number of keys
    - Can extend number of rounds (DES: 16)
  - Extensible AES seems to be significantly better than DES, but..
    - Human ingenuity is unpredicatble!

    => Need to incessantly search for better and better encryption algorithms

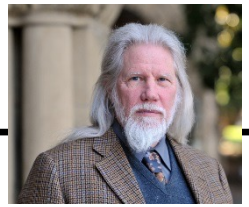
Motivation for PKE (1)

- So far - cryptosystems with secret keys
- Problems:
  - A lot of keys
    - $o(n^2)$ keys for n users (n * (n-1) /2 keys)
      — if each must be able to communicate with each
  - Distributing so many keys securely
  - Secure storage for the keys
    - User with n keys can't just memorize them
- Can have a system with significantly fewer keys?

  Yes!

Motivation for PKE (2)

Whitfield Diffie



- 1976 — Diffie and Hellman — new kind of cryptosystem:

  public key cryptosystem = asymmetric cryptosystem

  Martin E. Hellman

  - Key pairs: < $k_{PRIVATE}$, k_{PUBLIC}>
  - Each user owns one private key
  - Each user shares the corresponding public key with n-1 remaining users => n users share each public key
  - Only 2n keys for n users

    2n = n * (1 + n * 1/n)

    » Since public key is shared by n people: 1 "owner" + (n-1) others = n
    » 1/n since each part "owns" 1/n of the public key

    - Even if each communicates with each
    - Reduction from $o(n^2)$ to o(n) !
    - n key pairs are:

      <k_{PRIV-1}, k_{PUB-1} >, <k_{PRIV-2}, k_{PUB-2}>, …, <k_{PRIV-n}, k_{PUB-n}>

Characteristics of PKE (1)

- PKE requirements
  1. It must be computationally easy to encipher or decipher a message given the appropriate key
  2. It must be computationally infeasible to derive k_{PRIV} from k_{PUB}
  3. It must be computationally infeasible to determine k_{PRIV} from a chosen plaintext attack

[cf. Barbara Endicott-Popovsky, U. Washington]

Characteristics of PKE (2)

- Key pair characteristics
  - One key is inverse of the other key of the pair
    - i.e., it can undo encryption provided by the other:
      - $D(k_{PRIV}, E(k_{PUB}, P)) = P$
      - $D(k_{PUB}, E(k_{PRIV}, P)) = P$
  - One of the keys can be public since each key does only half of E ”+” D
    - As shown above – need both E and D to get P back

Characteristics of PKE (3)

- Two E/D possibilities for key pair <k_{PRIV}, k_{PUB} >
  - P = D(k_{PRIV}, E(k_{PUB}, P))
    - User encrypts msg with k_{PUB} (k_{PUB} "locks")
    - Recipient decrypts msg with k_{PRIV} (k_{PRIV} "unlocks")

  OR

  - P = D(k_{PUB}, E(k_{PRIV}, P)) (e.g., in RSA)
    - User encrypts msg with k_{PRIV} (k_{PRIV} "locks")
    - Recipient decrypts msg with key k_{PUB} (k_{PUB} "unlocks")
- Do we still need symmetric encryption (SE) systems?
  - Yes, PKEs are 10,000+ times (!) slower than SEs
    - PKEs use exponentiation – involves multiplication and division
    - SEs use bit operations (add,XOR< substitute, shift)–much faster

RSA Encryption (1)

- RSA = Rivest, Shamir, and Adelman (MIT), 1978
- **RSA** is one of the first practical public-key cryptosystems and is widely used for secure data transmission.
- Underlying hard problem:
  - Number theory – determining prime factors of a given (large) number (ex. factoring of small #: 5 → 5, 6 → 2 *3)
  - Arithmetic modulo n
- How secure is RSA?
  - So far remains secure (after all these years...)
  - Will quantum computing break it? TBD

RSA Encryption (2)

- In RSA:
  $P = E(D(P)) = D(E(P))$ (order of D/E does not matter)
  - More precisely: $P = E(k_E, D(k_D, P)) = D(k_D, E(k_E, P))$

- Encryption: $C = P^e \bmod n$ $K_E = e$
  - Given C, it is very difficult to find P without knowing K_D

- Decryption: $P = C^d \bmod n$ $K_D = d$