

Data Encryption Standard (DES)

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The Story So Far

- ▶ Mechanical ciphers like Enigma allowed much more complex algorithms to be used for encryption - see the optional lecture slides.
- ▶ They still didn't necessarily ensure security.
- ▶ The advent of the computer allowed even more complex algorithms to be used, using the XOR operation in conjunction with more familiar methods of substitution and transposition.
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 - ▶ **Public Key Cryptography**
 - ▶ **DES**

Lecture Aims

1. Understand how the XOR operation works.
2. Get a sense of how DES operates.

XOR: Exclusive-OR

- ▶ There are various ways to write the exclusive-OR. We might write x XOR y , or in logical notation $x \oplus y$. (Even sometimes $\underline{\vee}$.)
- ▶ It is described by the truth table below:

x	y	$x \oplus y$
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- ▶ This is the same as performing modular arithmetic using modulus 2:
 $0 + 0 = 0 = 1 + 1 \bmod 2$ and $1 + 0 = 1 = 0 + 1 \bmod 2$.

Bitwise XOR

x	y	$x \oplus y$
0	0	0
0	1	1
1	0	1
1	1	0

- ▶ We can apply this operator to whole strings of bits.
- ▶ For example, calculating $1010 \oplus 1011$ we perform XOR on the bits individually.
- ▶ So $1010 \oplus 1011 = 0001$.
- ▶ Digital data is generally stored in binary or hex, using bits, so this type of operation is well-suited for implementation in a computer-aided cipher scheme.

ASCII: American Standard Code for Information Interchange

DEC	OCT	HEX	BIN	Symbol	Description
65	101	41	01000001	A	Uppercase A
66	102	42	01000010	B	Uppercase B
67	103	43	01000011	C	Uppercase C
68	104	44	01000100	D	Uppercase D
69	105	45	01000101	E	Uppercase E
70	106	46	01000110	F	Uppercase F
71	107	47	01000111	G	Uppercase G

- ▶ A standard way to encode text and other characters. Each character is represented by a 7-bit binary string.
- ▶ Microsoft Excel uses 8-bit ANSI as above - not *quite* the same mapping of characters to strings.

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- ▶ Encryption is performed via the XOR operation and the key is then discarded.
- ▶ Shannon and Kotelnikov had both showed that this encryption scheme is *theoretically* unbreakable.

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 1. There is a problem generating a truly random sequence. Computers can never produce truly random numbers, only **pseudo-random** numbers, which are prone to attack.
 2. It requires a very long key which is computationally expensive to produce and difficult to distribute securely.
 3. A new key is required each time.

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- ▶ Dataseal → Demonstration Cipher → Demon → Lucifer → DES.
- ▶ Made the official worldwide standard in 1977.

DES: A Controversial Choice

- ▶ A large key size or length is an important part of a secure cryptographic system.
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- ▶ Expected to be used for 10 years from 1977. Triple-DES, or 3DES, developed in 1981 to be more secure, but is now finally disallowed as of 2023.

Block Ciphers vs. Stream Ciphers

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- ▶ DES and many modern ciphers are a form of **block cipher**: how letters are encrypted depends on the letters around them.

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- ▶ **Confusion**: Obscures the relationship between the key and the ciphertext - typically achieved with substitution.
- ▶ **Diffusion**: Spreads the influence of one plaintext bit over many ciphertext bits to hide statistical properties of the plaintext - typically achieved with transposition.
- ▶ **Multiple Rounds**: Intended to amplify the effect of confusion and diffusion.

Generating a Key

- ▶ Keys in DES are of length 56, but are expanded by **parity bits** to be 64 bits.

0101100 0001111 1011110 1001010 1101001 1010010 0101001 1110101

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- ▶ We put an extra bit on the *right* to make an *odd* number of 1s in each 8-bit byte:

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- ▶ In hex this is $0101\ 1000_2 = 58_{16}$.

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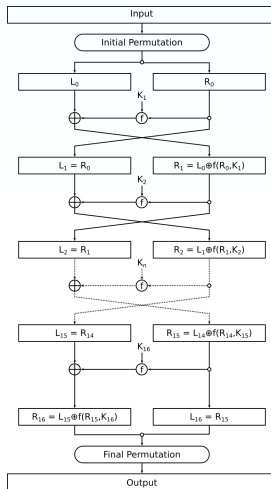
- ▶ In hex this is $0101\ 1000_2 = 58_{16}$.
- ▶ This is done for all bytes, which eventually gives the key as:

$K = 0101100\mathbf{0}\ 0001111\mathbf{1}\ 1011110\mathbf{0}\ 1001010\mathbf{0}\ 1101001\mathbf{1}\ 10100100\ 0101001\mathbf{0}\ 1110101\mathbf{0}$

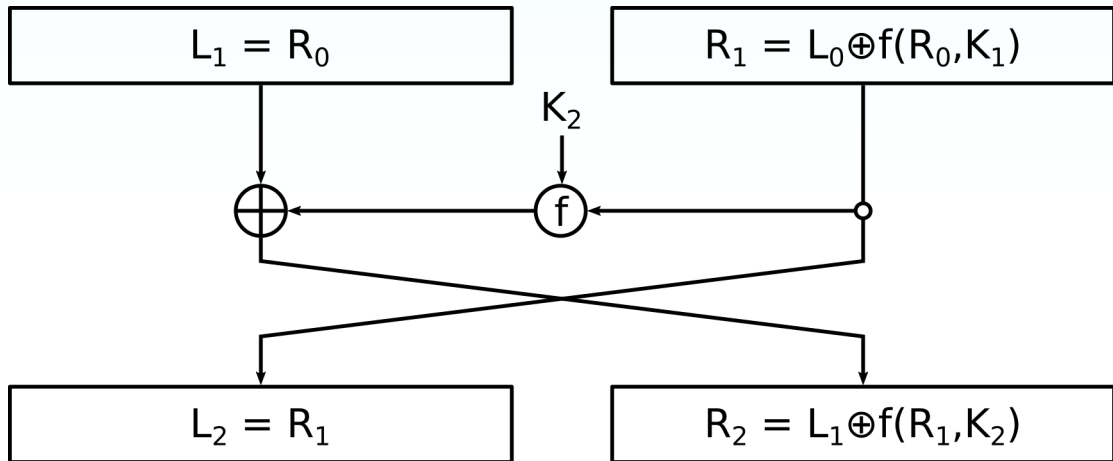
$K = 58\ 1F\ BC\ 94\ D3\ A4\ 52\ EA.$

- ▶ DES consists of 16 **rounds**, each using a 48-bit **round key** K_i derived from the original 56-bit key K .

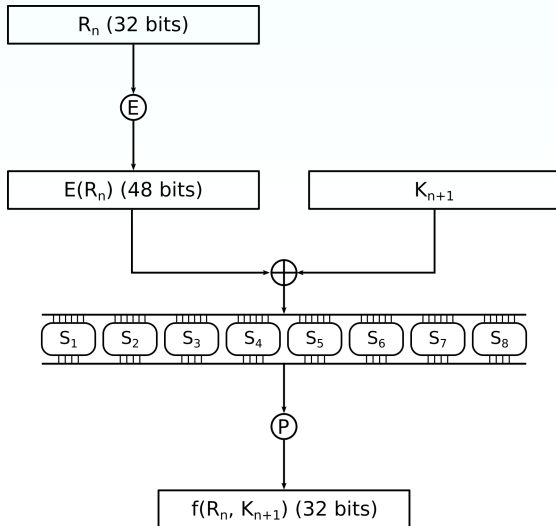
DES Scheme



DES Scheme: Single Round



DES Scheme: Mangler Function



DES Scheme: Right Expansion

A 32-bit *right half* is expanded to 48-bits in the following way, by repeating some of the bits.

32	1	2	3	4	5
4	5	6	7	8	9
8	9	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	30	31	32	1

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28	29	30	31	32	1

For example, if $R = 0000\ 0001\ 0010\ 0011\ 0100\ 0101\ 0110\ 0111$, then

$$E(R) = 100000\ 000010\ 100100\ 000110\ 101000\ 001010\ 101100\ 001110.$$

DES Scheme: XOR with Round Key

After the right half is expanded, it is XORed with the current round key. E.g., the first 48-bit round key K_1 from our example key is

001001 111010 000101 101001 111001 011000 110111 011010.

When XORed with the expanded right half

100000 000010 100100 000110 101000 001010 101100 001110

we get

101001 111000 100001 101111 010001 010010 011011 010100.

DES Scheme: S-Boxes

S_7	Column Number															
Row No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	4	11	2	14	15	0	8	13	3	12	9	7	5	10	6	1
1	13	0	11	7	4	9	1	10	14	3	5	12	2	15	8	6
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$$K_1 \oplus E(R) = 100111\ 100010\ 101001\ 010011\ 010100\ 000110\ 011110\ 100100.$$

- Each block passes through a separate S-box, or **substitution box**.

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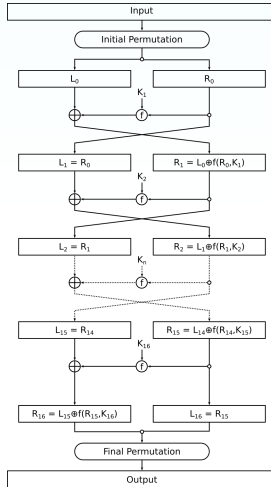
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- ▶ Block seven (011110) becomes $(00, 1111) = (0, 15)$, giving $1 = 0001$.

DES Scheme



Feistel System and Decryption

- ▶ The DES scheme is an example of a **Feistel system**:
 - ▶ Ladder structure;
 - ▶ Input split into left and right halves;
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 - ▶ The halves are swapped over.
- ▶ To decrypt the ciphertext: retrace all the steps in the 16 rounds using the same key K , but with the round keys used in the opposite order.

Breaking DES

- ▶ DES was expected to be used for 10 years: 1977-1987.
- ▶ It remained the standard **secret key** encryption method until 1998.
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- ▶ In the 1980s rumours circulated that intelligence agencies had already built machines to search for DES keys.
- ▶ By the 2000s, computers were 100,000 times more powerful making brute force attacks quite straightforward.
- ▶ A (second) challenge was issued in 1998 by the RSA Laboratory, with a \$10,000USD prize:
 - ▶ Electronic Frontier Foundation's DES Cracker, working as a botnet, took only 3 days to crack DES.
 - ▶ The previous record was 39 days.
 - ▶ In 1999, a network of 100,000 PCs on the Internet cracked DES in 22 hours and 15 minutes.
 - ▶ DES needed to be replaced.

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- ▶ The idea here is that this would double the keyspace from 2^{56} options to 2^{112} .
- ▶ Unfortunately, due to **meet-in-the-middle attacks**, this actually only increased the number of keys to 2^{57} .

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- ▶ Often used with two keys, setting $K_1 = K_3$, but keeping K_2 independent.
- ▶ Much stronger against meet-in-the-middle attacks.

Triple-DES: 3DES

- ▶ 3DES encryption was the standard for ATMs: all machines had to be compliant by 2005.
- ▶ CVE-2016-2183 (Critical Vulnerabilities and Exposures) released in 2016 describes the 'Sweet32' attack (a type of **birthday attack**, which shows that even Triple DES was not sufficient any more).



Tutorials

In the tutorial this week we will:

- ▶ Create a spreadsheet to perform bitwise XOR encryption.
- ▶ Expand this to XOR whole words at a time.
- ▶ Use the remaining time to make a start on the coursework. We've seen everything we need for Questions 1 and 2 of Section B.

Just the tip of the iceberg

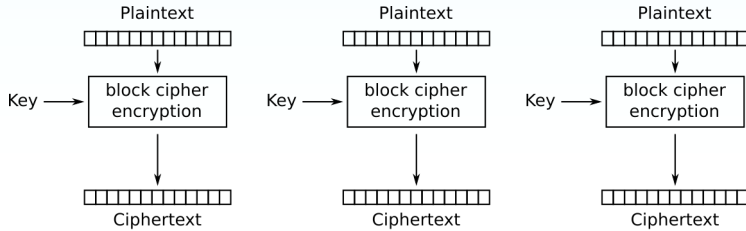
One-time Pad	Blowfish	Autokey	RSA	Pigpen	Scytale
McEliece	Atbash	DES	Vigenère	Zig Zag	ElGamal
Beaufort	ECC	Hill	Chaocipher	Twofish	Alphabet
Caesar	Rail Fence	ROT13	SPHINCS	RC4	Enigma
Alberti	Cramer-Shoup	Kyber	Playfair	AES	Affine

Modes of Operation

Five standard ways of implementing DES:

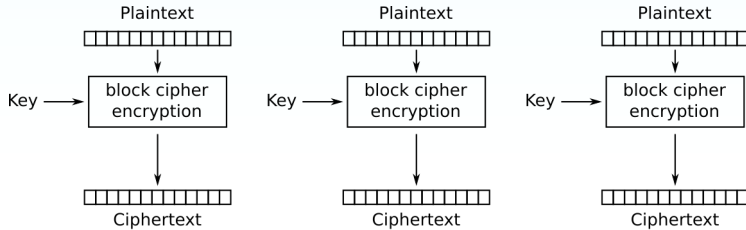
- ▶ Mode 1: Electronic Code Book
- ▶ Mode 2: Cipher Block Chaining
- ▶ Mode 3: Cipher Feedback Mode
- ▶ Mode 4: Output Feedback Mode
- ▶ Mode 5: Counter Mode

Modes of Operation: Electronic Code Book



Electronic Codebook (ECB) mode encryption

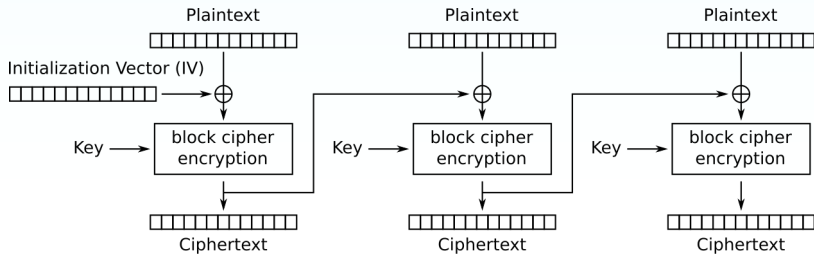
Modes of Operation: Electronic Code Book



Electronic Codebook (ECB) mode encryption

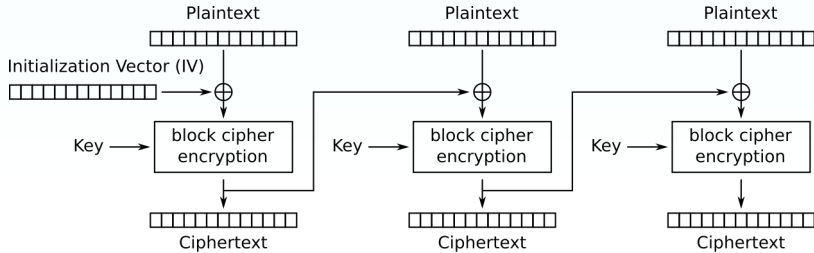
ECB encrypts the blocks one after another, but is vulnerable to attack for long messages because of plaintext patterns.

Modes of Operation: Cipher Block Chaining



Cipher Block Chaining (CBC) mode encryption

Modes of Operation: Cipher Block Chaining



Cipher Block Chaining (CBC) mode encryption

CBC uses the previous ciphertext block XORed with the new plaintext block before proceeding with encryption. An Initialisation Vector (IV) is used to XOR the first plaintext block. ECB is better at hiding plaintext patterns than ECB.

Modes of Operation: ECB vs Other Modes



Modes of Operation: ECB vs Other Modes



Modes of Operation: ECB vs Other Modes

