Data Encryption Standard (DES)

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  - **Public Key Cryptography**
  - **DES**

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- This is in fact 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

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- So $1\,0\,1\,0 \oplus 1\,0\,1\,1 = 0\,0\,0\,1$.

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- 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
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- 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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- Then a random key of 0s and 1s is chosen which is the same length as the plaintext.
- 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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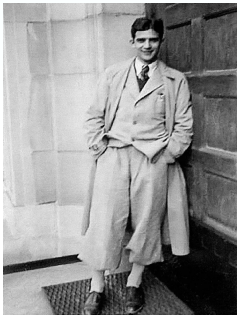
  3. A new key is required each time.

Development of DES



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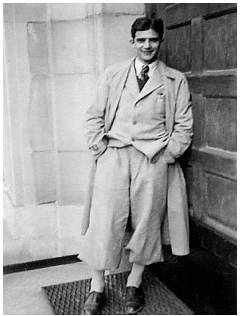

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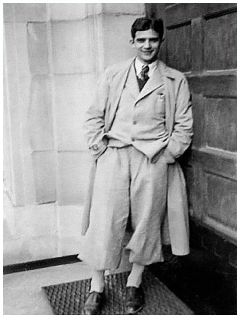

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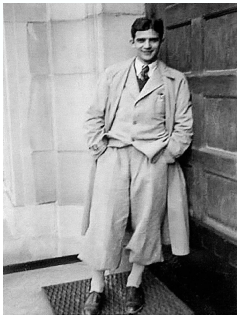

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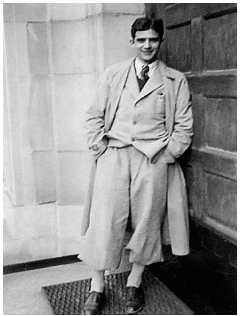

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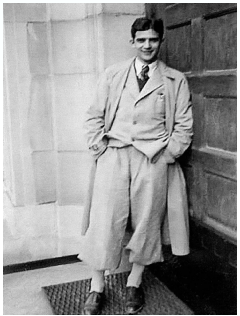

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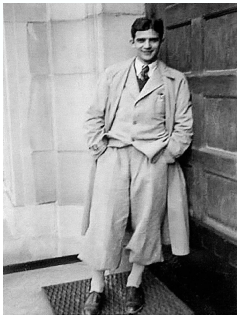

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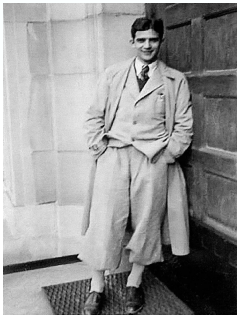

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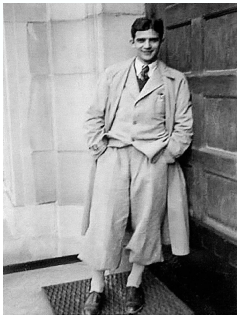

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- Made the official worldwide standard in 1977.

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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 also disallowed as of 2023.

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- **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.

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

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$$01011000.$$

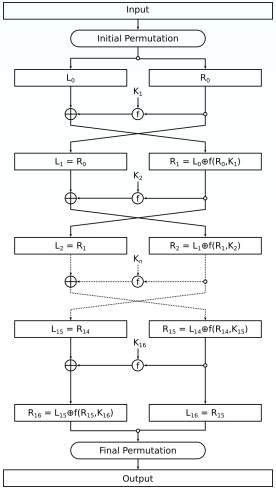
- In hex this is $0101\,1000_2 = 58_{16}$.
- This is done for all bytes, which eventually gives the key as:

$$K = 01011000\,00011111\,10111100\,10010100\,11010011\,10100100\,01010010\,11101010$$

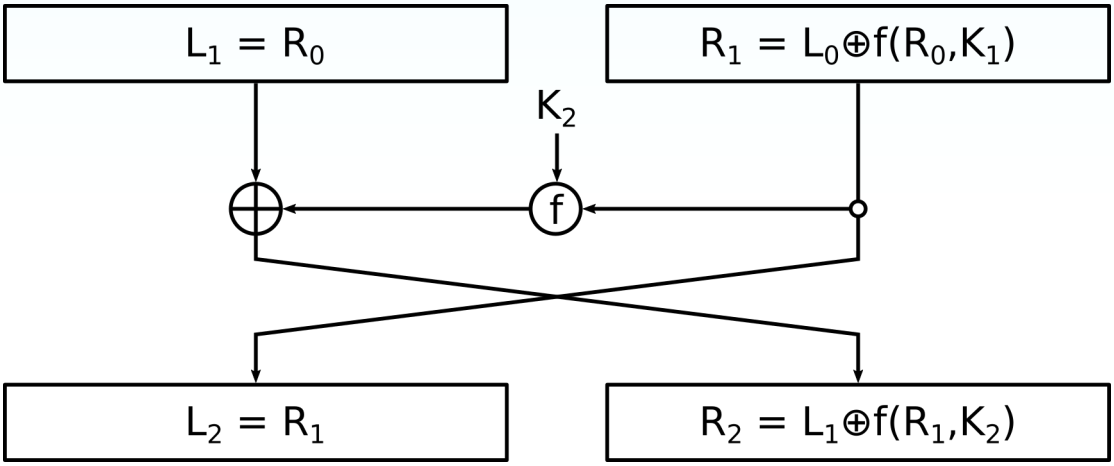
$$K = 58 \quad 1F \quad BC \quad 94 \quad D3 \quad A4 \quad 52 \quad EA.$$

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

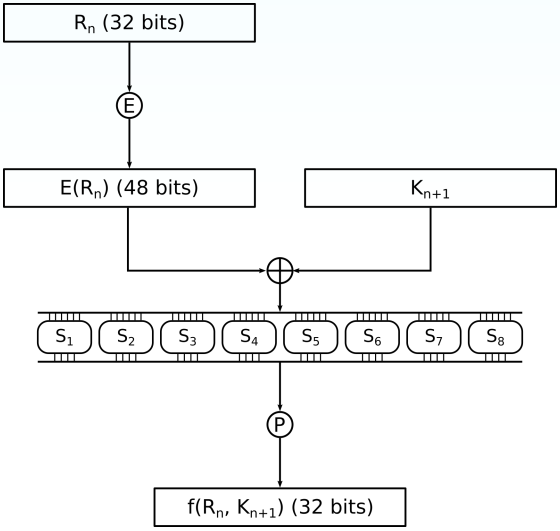
DES Scheme


Input
Initial Permutation
L_0
R_0
K_1
f
$L_1 = R_0$
$R_1 = L_0 \oplus f(R_0, K_1)$
K_2
f
$L_2 = R_1$
$R_2 = L_1 \oplus f(R_1, K_2)$
K_n
f
$L_{15} = R_{14}$
$R_{15} = L_{14} \oplus f(R_{14}, K_{15})$
K_{16}
f
$R_{16} = L_{15} \oplus f(R_{15}, K_{16})$
$L_{16} = R_{15}$
Final Permutation
Output

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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20	21	22	23	24	25
24	25	26	27	28	29
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
2	1	4	11	13	12	3	7	14	10	15	6	8	0	5	9	2
3	6	11	13	8	1	4	10	7	9	5	0	15	14	2	3	12

$$K_1 \oplus E(R) = 100111\,100010\,101001\,010011\,010100\,000110\,011110\,100100.$$

- Each block passes through a separate S-box.

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- Each block passes through a separate S-box.
- A block $b_1 b_2 b_3 b_4 b_5 b_6$ is split into a pair $(b_1 b_6, b_2 b_3 b_4 b_5)$.

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- Each block passes through a separate S-box.
- A block $b_1b_2b_3b_4b_5b_6$ is split into a pair $(b_1b_6, b_2b_3b_4b_5)$.
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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
2	1	4	11	13	12	3	7	14	10	15	6	8	0	5	9	2
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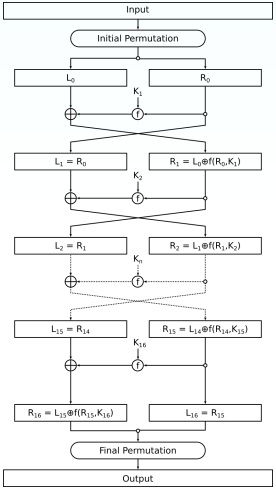
- Block seven (011110) becomes $(00, 1111) = (0, 15)$, giving $1 = 0001$.

DES Scheme


Input
Initial Permutation
L_0
R_0
K_1
f
$L_1 = R_0$
$R_1 = L_0 \oplus f(R_0, K_1)$
K_2
f
$L_2 = R_1$
$R_2 = L_1 \oplus f(R_1, K_2)$
K_n
f
$L_{15} = R_{14}$
$R_{15} = L_{14} \oplus f(R_{14}, K_{15})$
K_{16}
f
$R_{16} = L_{15} \oplus f(R_{15}, K_{16})$
$L_{16} = R_{15}$
Final Permutation
Output

Feistel System and Decryption

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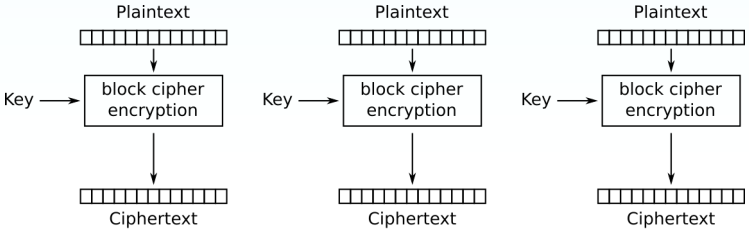
  - The halves are swapped over.
- To decrypt the ciphertext: retrace all the steps in the 16 rounds using the same key K, but with the round keys used in the opposite order.

Modes of Operation

Five standard ways of implementing DES:

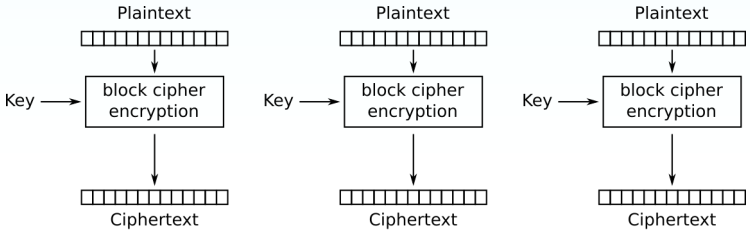
- Mode 1: Electronic Code Book
- Mode 2: Cipher Block Chaining
- Mode 3: Cipher Feedback Mode
- Mode 4: Output Feedback Mode
- Mode 5: Counter Mode

Modes of Operation: Electronic Code Book



Electronic Codebook (ECB) mode encryption

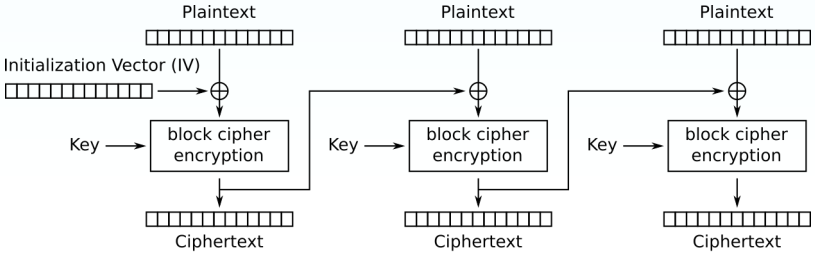
Modes of Operation: Electronic Code Book



Electronic Codebook (ECB) mode encryption

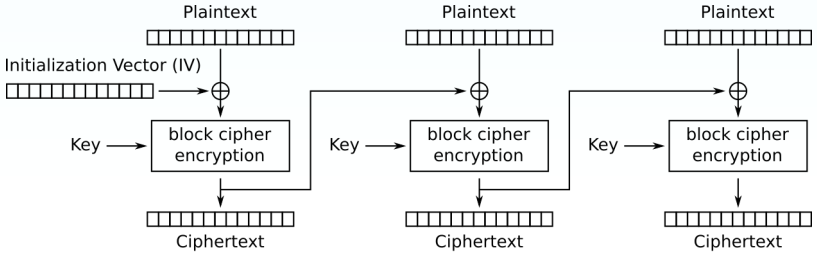
ECB encrypts the blocks one after another, but is vulnerable to attack for long messages because of plaintext patterns.

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 `XOR`ed 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

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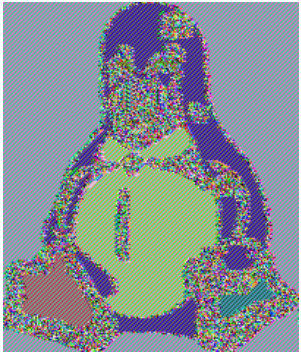

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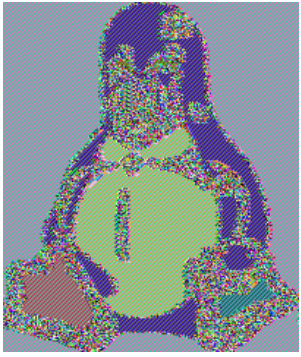

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  - DES needed to be replaced.

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- 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.

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- All applications of 3DES were to cease by 2023.
- DES finally superseded by the Advanced Encryption Standard (AES).

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.