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**

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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 $\veebar$.)
- It is described by the truth table below:

x	y	$x \oplus y$
0	0	0
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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 $1\,0\,1\,0 \oplus 1\,0\,1\,1 = 0\,0\,0\,1$.
- 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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- 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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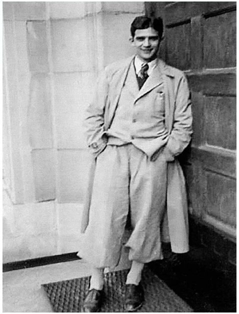
- Theoretically unbreakable, but not really very practical.
  1. There is a problem generating a truly random sequence. Computers can never produce truly random numbers, only **pseudo-random** numbers, which are prone to attack.
  2. It requires a very long key which is computationally expensive to produce and difficult to distribute securely.
  3. A new key is required each time.

Development of DES



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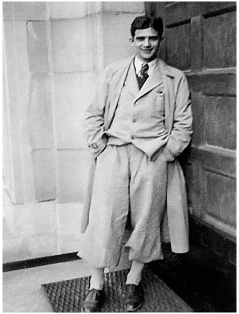

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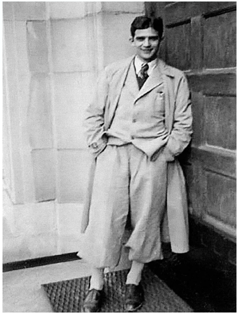

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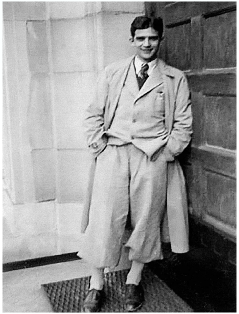

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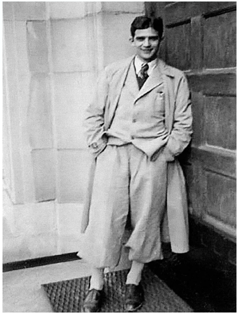

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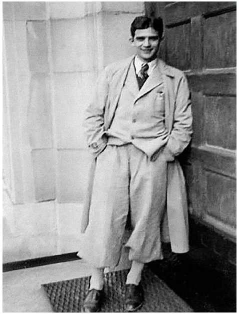

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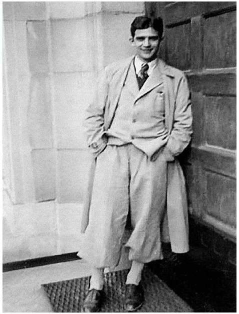

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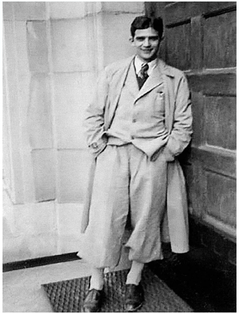

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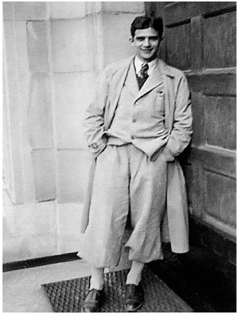

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- The National Bureau of Standards held a competition in 1974: IBM submitted Lucifer.
- Dataseal → Demonstration Cipher → Demon → Lucifer → DES.
- Made the official worldwide standard in 1977.

DES: A Controversial Choice

- A large key size or length is an important part of a secure cryptographic system.
- Some people, such as Whitfield Diffie and Martin Hellman, believed the DES key size to be too small to be secure.
- It was 56 bits compared to IBM's original Lucifer key size of 128 bits.

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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

- The ciphers we have seen so far have all been **stream ciphers**: each letter is encrypted separately.
- 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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- The first seven bits (on the left) are 0101100.
- 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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$$0101100\mathbf{0}.$$

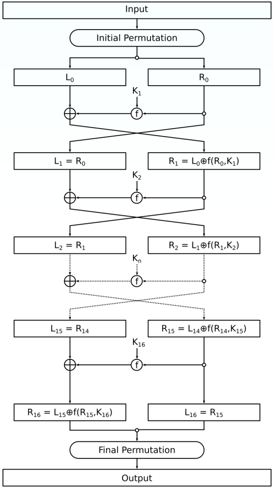
- In hex this is $0101\,1000_2 = 58_{16}$.
- This is done for all bytes, which eventually gives the key as:

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

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

- 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

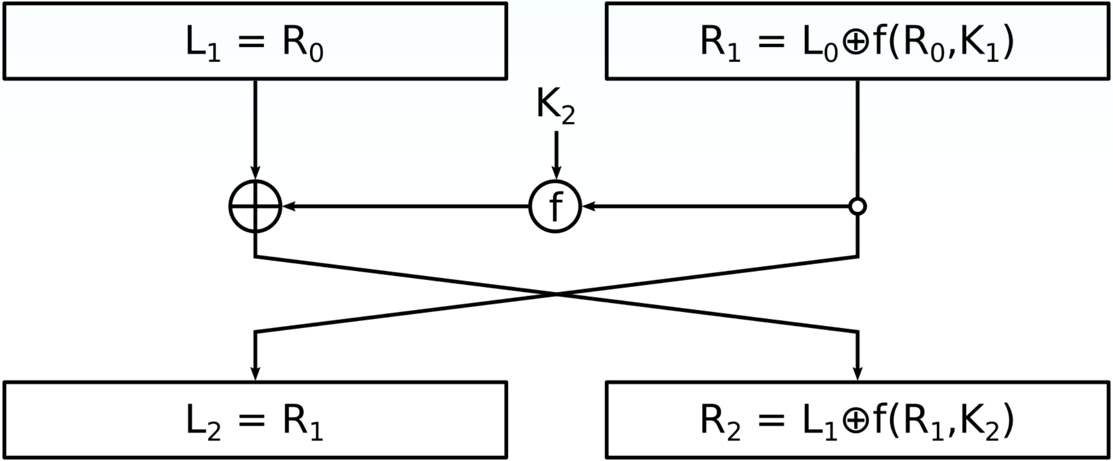
$R_{16} = L_{15} \oplus f(R_{15}, K_{16})$

$L_{16} = R_{15}$

Final Permutation

Output

DES Scheme: Single Round



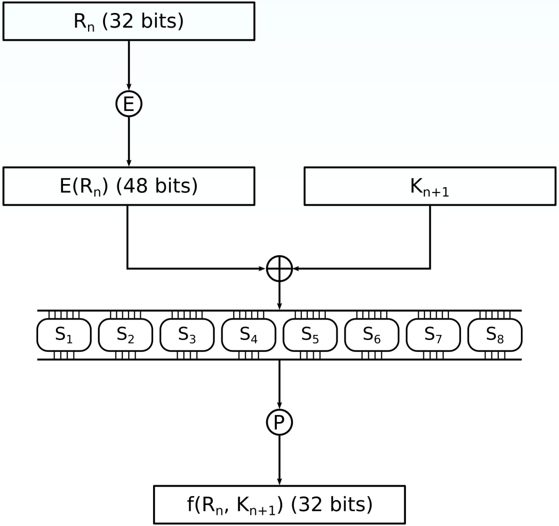
$L_1 = R_0$

$R_1 = L_0 \oplus f(R_0,K_1)$

$L_2 = R_1$

$R_2 = L_1 \oplus f(R_1,K_2)$

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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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, or **substitution box**.

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

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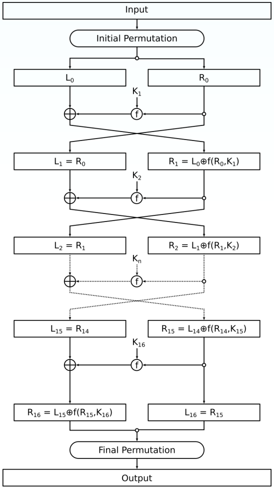
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K_2
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K_n
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K_{16}
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$R_{16} = L_{15} \oplus f(R_{15}, K_{16})$
$L_{16} = R_{15}$
Final Permutation
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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    - A round function of one half is computed and combined with the other half using bitwise `XOR`;
    - 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.
- Ongoing debates about security of DES focussed on the short key length.
- Brute force attacks were theoretically possible, but the hardware in the 1970s would take too long to make this an efficient attack.

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- Brute force attacks were theoretically possible, but the hardware in the 1970s would take too long to make this an efficient attack.
- 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 $\$10,000$USD 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.

Double-DES: 2DES

- How do we make DES more secure?

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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}.

Triple-DES: 3DES

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Triple-DES: 3DES

- How do we make DES more secure? Run it *three* times.

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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

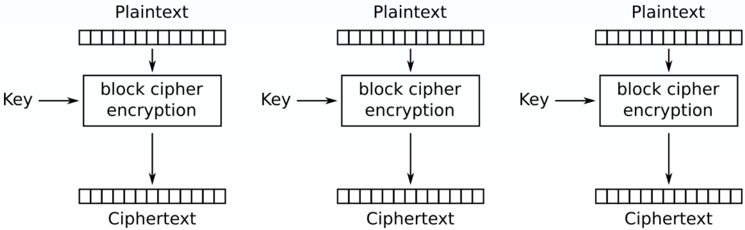
One-time Pad	Blowfish	Autokey	RSA	Pigpen	Scytale
McEliece	Atbash	DES	Vigenère	Zig Zag	ElGamal
Beaufort	ECC	Hill	Chaocipher	Twofish	Alphabet
Caesar	Rail Fence	ROT13	SPHINCS	RC4	Enigma
Alberti	Cramer-Shoup	Kyber	Playfair	AES	Affine

Modes of Operation

Five standard ways of implementing DES:

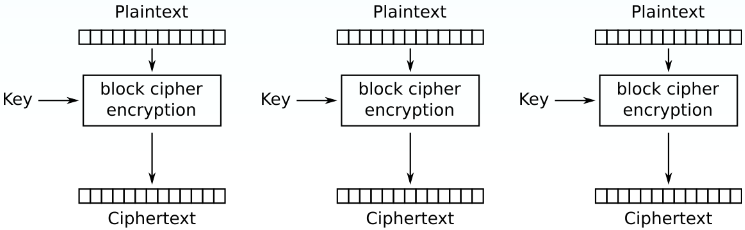
- Mode 1: Electronic Code Book
- Mode 2: Cipher Block Chaining
- Mode 3: Cipher Feedback Mode
- Mode 4: Output Feedback Mode
- Mode 5: Counter Mode

Modes of Operation: Electronic Code Book



Electronic Codebook (ECB) mode encryption

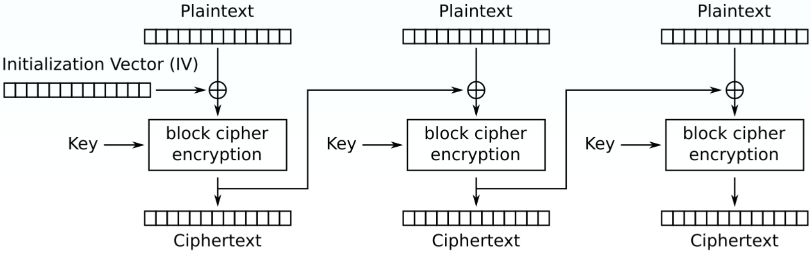
Modes of Operation: Electronic Code Book



Electronic Codebook (ECB) mode encryption

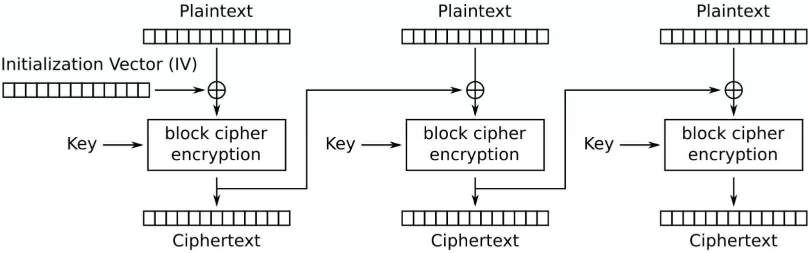
ECB encrypts the blocks one after another, but is vulnerable to attack for long messages because of plaintext patterns.

Modes of Operation: Cipher Block Chaining



Cipher Block Chaining (CBC) mode encryption

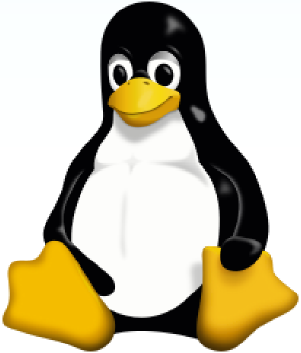
Modes of Operation: Cipher Block Chaining



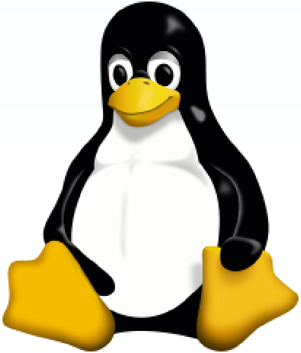
Cipher Block Chaining (CBC) mode encryption

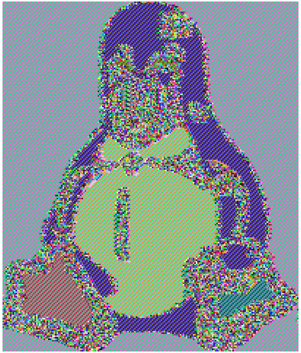
CBC uses the previous ciphertext block `XOR`ed with the new plaintext block before proceeding with encryption. An Initialisation Vector (IV) is used to `XOR` the first plaintext block. ECB is better at hiding plaintext patterns than ECB.

Modes of Operation: ECB vs Other Modes



Modes of Operation: ECB vs Other Modes





Modes of Operation: ECB vs Other Modes