

Cryptography III: Symmetric Ciphers

Computer Security Lecture 4

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Outline

Stream ciphers

Block ciphers

DES and Rijndael

Summary

Stream ciphers and block ciphers

Symmetric-key encryption schemes are often characterised as *stream ciphers* or *block ciphers*, but the distinction can be fuzzy.

- ▶ A **stream cipher** is an encryption scheme which treats the plaintext symbol-by-symbol (e.g., by bit or byte);
- ▶ security in a stream cipher lies in a changing **keystream** rather than the encryption function, which may be simple.
- ▶ A **block cipher** is an encryption scheme which breaks up the plaintext message into *blocks* of a fixed length (e.g., 128 bits), and encrypts one block at a time;
- ▶ the block encryption function is a complex function parameterised on a fixed size **key**.

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Stream ciphers

Typically, $\mathcal{M} = \mathcal{C} = \mathcal{A}$ and a stream of symbols

$$m_1 \ m_2 \ m_3 \ \dots$$

is encrypted using a keystream

$$e_1 \ e_2 \ e_3 \ \dots$$

to generate

$$E_{e_1}(m_1) \ E_{e_2}(m_2) \ E_{e_3}(m_3) \ \dots$$

Stream ciphers may be

- ▶ **synchronous** (keystream generated independently of the plaintext and ciphertext), or
- ▶ **self-synchronizing** (the keystream is generated as a function of the key and a fixed amount of previous ciphertext).

Vernam cipher and one-time pad

- ▶ The **Vernam cipher** is a stream cipher defined on the alphabet $\mathcal{A} = \{0, 1\}$, with a key stream also of binary digits.
- ▶ Each symbol m_i in the message is encoded using the corresponding symbol k_i of the key stream, using exclusive-or:

$$c_i = m_i \oplus k_i.$$

- ▶ Because $(a \oplus b) \oplus b = a$, the decryption operation is identical:

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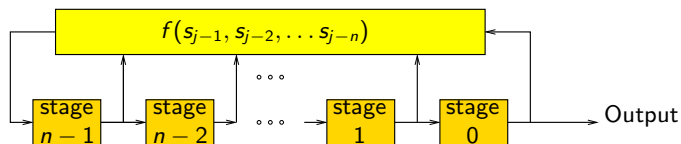
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If the key string is randomly chosen, and never reused, then this cipher is called a **one-time pad**. Claude Shannon proved that this cipher is unconditionally secure. Unfortunately, to guarantee this, it requires a true random source for key bits (hard to come by), and a key stream as long as the message. This makes it impractical for most applications. It used to be used for high security communications between Washington and Moscow.

Feedback Shift Registers

- ▶ More practical than the one-time pad would be to use a pseudorandom keystream, which is *seeded* with a much shorter key. **Feedback shift registers** (FSRs) are the basic component of many keystream generators, used to produce pseudorandom bit streams.
- ▶ An FSR of length n consists of n 1-bit register stages connected together, whose contents \vec{s} are inputs to a boolean function f . At each tick, the contents are shifted right, and f calculates the feedback digit.



- ▶ If the initial state is $[s_{n-1}, \dots, s_0]$, then the output sequence s_0, s_1, \dots is determined by the equation:
$$s_j = f(s_{j-1}, s_{j-2}, \dots, s_{j-n}) \text{ for } j \geq n.$$

Linear Feedback Shift Registers

- ▶ In a n -length LFSR, the feedback function f is set by a n -degree *connection polynomial* C with binary coefficients c_i

$$C(X) = 1 + c_1X + c_2X^2 \dots + c_nX^n$$

this determines the feedback function, as:

$$s_j = (c_1s_{j-1} + c_2s_{j-2} + \dots + c_ns_{j-n}) \bmod 2 \quad \text{for } j \geq n.$$

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- ▶ In practice, some controlled **non-linearity** is added by either non-linear filtering or composition of LFSRs, or LFSR-controlled clocking.

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Old Time Cryptanalysis

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If I saw anything that looked like a German word I had to stop the machine; someone would come and note the position where I had stopped and transfer the section of script to their machines for further investigation. I did this work from July 1943 to May 1945 and earned 3 pounds a week. I heard people say that they thought it must be very interesting work but in fact I found it extremely boring.

Miss Frances Joyce Woodward, a decoder at Bletchley Park [see

BBC People's War]

Simple substitution ciphers

A *simple substitution cipher* is a block cipher for arbitrary block length t . It swaps each letter for another letter, using a permutation of the alphabet.

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- ▶ For each $e \in \mathcal{K}$ define E_e by applying the permutation e to each letter in the plaintext block:

$$E_e(m) = e(m_1)e(m_2) \cdots e(m_t) = c$$

where $m \in \mathcal{M}$ and $m = m_1 m_2 \cdots m_t$.

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For each $d \in \mathcal{K}$ we define E_d in exactly the same way,

$$D_d(c) = d(c_1)d(c_2) \cdots d(c_t).$$

- ▶ Key pairs are permutations and their inverses, so $d = e^{-1}$, and

$$D_d(c) = e^{-1}(c_1)e^{-1}(c_2) \cdots e^{-1}(c_t) = m_1m_2 \cdots m_t = m.$$

Simple substitution ciphers, cont'd

- ▶ The **Caesar cipher** is a simple substitution cipher which replaces $A \rightarrow D$, $B \rightarrow E$, $C \rightarrow F$, \dots , $X \rightarrow A$, $Y \rightarrow B$, $Z \rightarrow C$.

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Simple substitution ciphers are **insecure**, even when the key space is large. The reason is that the distribution of letter frequencies is preserved in the ciphertext, which allows easy cryptanalysis with a fairly small amount of ciphertext and known properties of plain text (e.g., the relative frequencies of letters in English text).

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This emphasises what should be an obvious point: a **large keyspace does not guarantee a strong cipher**. For the alphabet A-Z, the size of the key space for this cipher is $26! \approx 2^{88}$, large enough to prevent brute force attacks by today's standards. But the cipher is easy to break.

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- ▶ The corresponding decryption key is $d = (p_1^{-1}, \dots, p_t^{-1})$.

Polyalphabetic substitution ciphers, cont'd

- ▶ The **Vigenère cipher** has a block-length of 3, and uses the permutations $e = (p_1, p_2, p_3)$ where p_1 rotates each letter of the alphabet three places to the right, p_2 rotates seven positions, and p_3 ten positions (e may be represented as the word DHK). For example:

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Polyalphabetic substitution ciphers have the advantage over simple substitution ciphers that symbol frequencies are not preserved: a single letter may be encrypted to several different letters, in different positions. However, cryptanalysis is still straightforward, by first determining the block size, and then applying frequency analysis by splitting the letters into groups which are encrypted with the same permutation. So polyalphabetic substitutions are certainly **not secure**.

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This cipher again preserves letter frequencies, which allows easy cryptanalysis. So it is **not secure**. These block ciphers so far are not useful by themselves, but get interesting when combined. A good cipher should add both **confusion** by substitution transformations and **diffusion** by transpositions. Confusion obscures the relationship between the key and the ciphertext. Diffusion spreads out redundancy in the plaintext across the ciphertext. Modern block ciphers apply *rounds* consisting of substitution and transposition steps.

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- ▶ Involutions (functions that are their own inverse) are particularly useful in constructing product ciphers. The favourite is XOR: $f(x) = x \oplus c$.

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$$L_{i+1} = R_i \quad R_{i+1} = L_i \oplus f(K_i, R_i).$$

The inverse operation is:

$$R_i = L_{i+1} \quad L_i = R_{i+1} \oplus f(K_i, L_{i+1}).$$

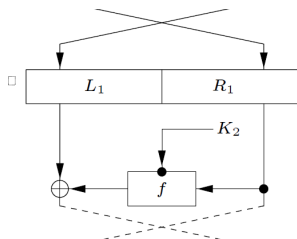
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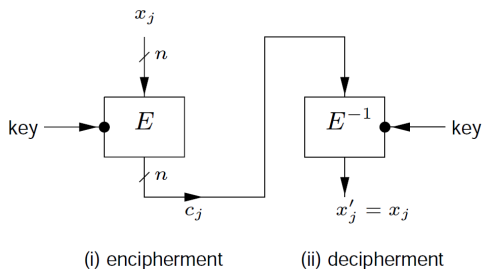
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Modes for block ciphers: ECB

- ▶ Block ciphers can be used in various **modes**. **Important reading exercise**: compare the *security*, *efficiency*, *inbuilt data integrity*, and *error recovery* of these different modes.
- ▶ **ECB**: *electronic codebook mode*. Each block of plaintext x_j is enciphered independently.

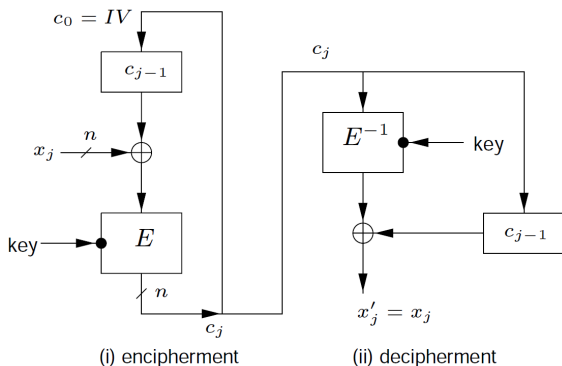


- ▶ This is the simplest mode, but it has obvious failings.

Modes for block ciphers: CBC

- ▶ **CBC**: *cipherblock chaining mode*. Each plaintext block x_j is XORed with the previous ciphertext c_{j-1} block before encryption. An *initialization vector* (IV) (optionally secret, fresh for each message) is used for c_0 .

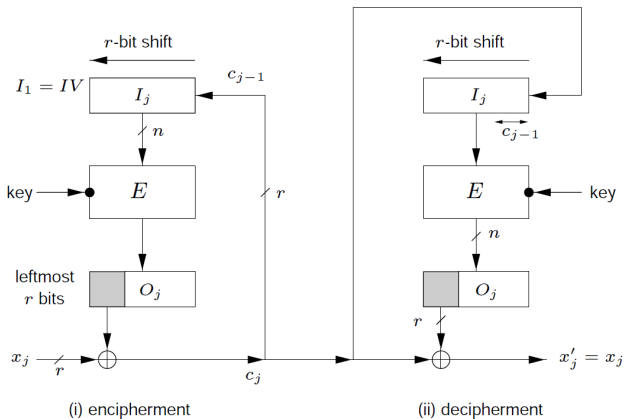
$$c_j = E_k(x_j \oplus c_{j-1}) \quad x_j = c_{j-1} \oplus E_k^{-1}(c_j)$$



Modes for block ciphers: CFB

- **CFB** *cipher-feedback mode*. Encryption function of block cipher used as self-synchronizing stream cipher for symbols of size up to block size.

$$c_j = x_j \oplus E_k(c_{j-1}) \quad x_j = c_j \oplus E_k(c_{j-1})$$



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Security of 3DES is not obvious: repeated encryption may not gain security (one-step DES is not closed, so it in fact does), and new attacks may be possible (**meet-in-the-middle attack**). With 3 independently chosen keys, security is roughly the same as expected with 2 keys.

DES

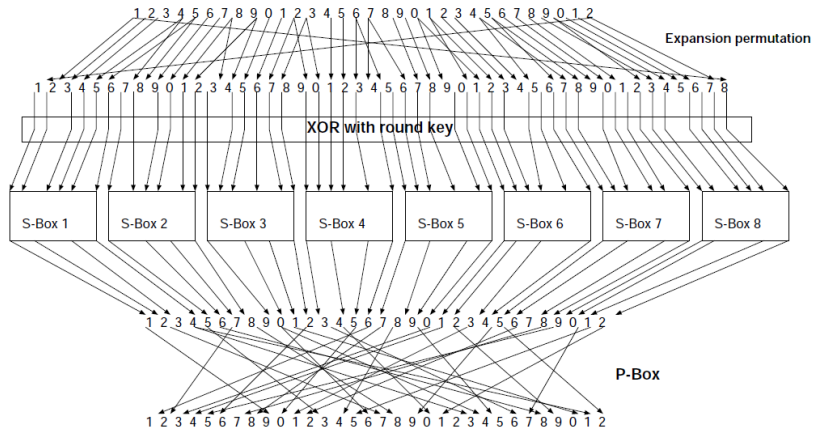
- ▶ **DES** is a block cipher based on Feistel's principle. Block-size is 64 bits, key-size 56 bits (+8 parity bits). Invented by IBM in 1970s, tweaked by NSA. Still widely used, esp. in financial sector. Much analysed.
- ▶ Main threat isn't cryptanalytic, but (slightly optimised) **exhaustive search** in small key-space. Remedied by **3DES** (triple DES), 3 keys:

$$C = E_{k_3}(D_{k_2}(E_{k_1}(P))) \quad P = D_{k_1}(E_{k_2}(D_{k_3}(C))).$$

Security of 3DES is not obvious: repeated encryption may not gain security (one-step DES is not closed, so it in fact does), and new attacks may be possible (**meet-in-the-middle attack**). With 3 independently chosen keys, security is roughly the same as expected with 2 keys.

- ▶ Several other DES variants, including **DESX**, using *whitening* keys k_1, k_2 as $C = E_k(P \oplus k_1) \oplus k_2$. (Used in Win2K encrypting FS).

Overview of DES internals [FIPS 46-3]



The Advanced Encryption Standard

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- ▶ Rijndael satisfied a number of requisite criteria for the AES:
 - ▶ **Security**: mathematical, cryptanalytic resistance; randomness;
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- ▶ Rijndael is built as a network of linear transformations and substitutions, with 10, 12 or 14 rounds, depending on key size.

Outline

Stream ciphers

Block ciphers

DES and Rijndael

Summary

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- ▶ **Skipjack**. NSA designed, once classified (key escrow and LEAF issue) and patented under a secrecy order; now public domain. Block size 64 bits, 80-bit key. Used in tamperproof **Clipper** and **Capstone** chips.

References

The DES diagram is from Smart, Chapter 8 and the block cipher diagrams are from Figure 7.1 in the HAC.

-  Alfred J. Menezes, Paul C. Van Oorschot, and Scott A. Vanstone, editors. *Handbook of Applied Cryptography*. CRC Press Series on Discrete Mathematics and Its Applications. CRC Press, 1997.
Online version at
<http://www.cacr.math.uwaterloo.ca/hac>.
-  Bruce Schneier. *Applied Cryptography*. John Wiley & Sons, second edition, 1996.
-  Nigel Smart. *Cryptography: An Introduction*. 3rd edition, 2008, at
http://www.cs.bris.ac.uk/~nigel/Crypto_Book/.

Recommended Reading

Chapters 7 and 8 of Smart.