Cryptography III: Symmetric Ciphers

Computer Security Lecture 4

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Outline

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**.

Outline

Stream ciphers

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

$$m_1 \; m_2 \; m_3 \; \cdots$$

is encrypted using a keystream

$$e_1 \; e_2 \; e_3 \; \cdots$$

to generate

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

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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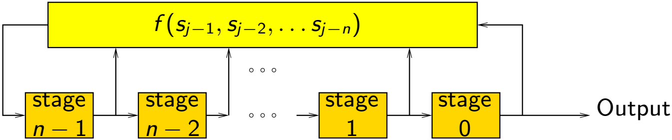
If the key string is randomly chosen, and never reused, then this cipher is called a **one-time pad**. Claude Shannon proved that this cipher is unconditionally secure. Unfortunately, to guarantee this, it requires a true random source for key bits (hard to come by), and a key stream as long as the message. 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 $[s_{n-1}, \ldots, s_0]$, then the output sequence $s_0, s_1, \ldots$ is determined by the equation: $s_j = f(s_{j-1}, s_{j-2}, \ldots s_{j-n})$ 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

$$C(X) = 1 + c_1 X + c_2 X^2 \ldots + c_n X^n$$

this determines the feedback function, as:

$$s_j = (c_1 s_{j-1} + c_2 s_{j-2} + \cdots + c_n s_{j-n}) \bmod 2 \qquad \text{for } j \geq n.$$

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- However, LFSRs are **insecure**. To break, find the length n, and then use a known-plaintext attack of length $2n$.
- 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 a week. I heard people say that they thought it must be very interesting work but in fact I found it extremely boring.

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

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

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

$$D_d(c) = e^{-1}(c_1)e^{-1}(c_2)\cdots e^{-1}(c_t) = m_1 m_2 \cdots m_t = m.$$

Simple substitution ciphers, cont'd

- The **Caesar cipher** is a simple substitution cipher which replaces $\mathtt{A} \to \mathtt{D}$, $\mathtt{B} \to \mathtt{E}$, $\mathtt{C} \to \mathtt{F}$, $\ldots$, $\mathtt{X} \to \mathtt{A}$, $\mathtt{Y} \to \mathtt{B}$, $\mathtt{Z} \to \mathtt{C}$.

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

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
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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: $f(x) = x \oplus c$.

Constructing block ciphers

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- The **Feistel principle** gives a way of constructing a cipher so that the same circuit is used for both encryption and decryption. A *round* in a Feistel cipher treats the input block in two halfs, L_i and R_i. It uses the right-hand half to modify the left, and then swaps:

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

  The inverse operation is:

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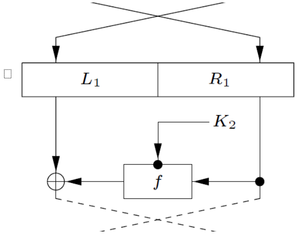
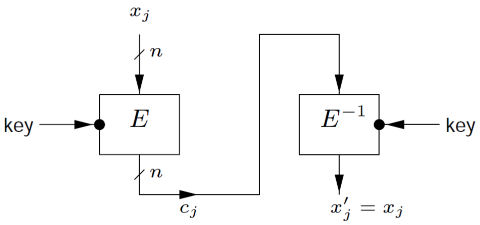


Modes for block ciphers: ECB

- 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.



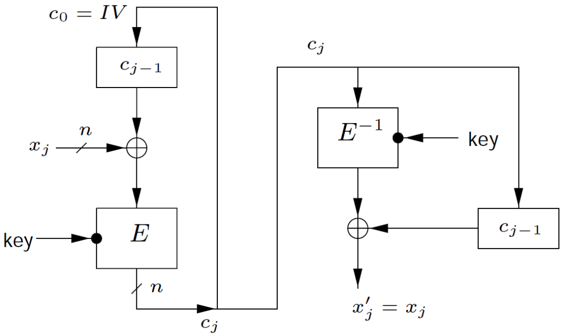
(i) encipherment (ii) decipherment

- 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.

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



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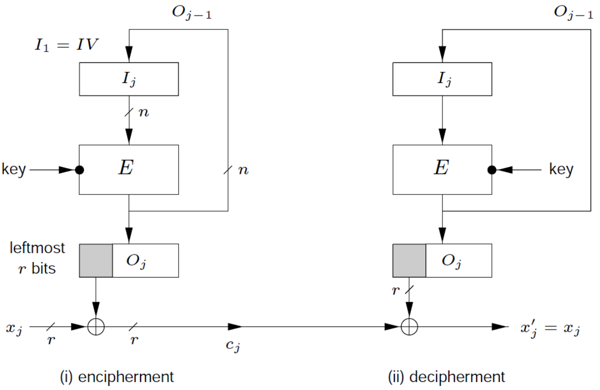
Modes for block ciphers: OFB

- **OFB**: *output-feedback mode*. Block cipher encryption function used as synchronous stream cipher (*internal feedback*).

$$c_j = x_j \oplus s_j; \; s_j = E_k(s_{j-1}) \qquad x_j = c_j \oplus s_j; \; s_j = E_k(s_{j-1})$$



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.

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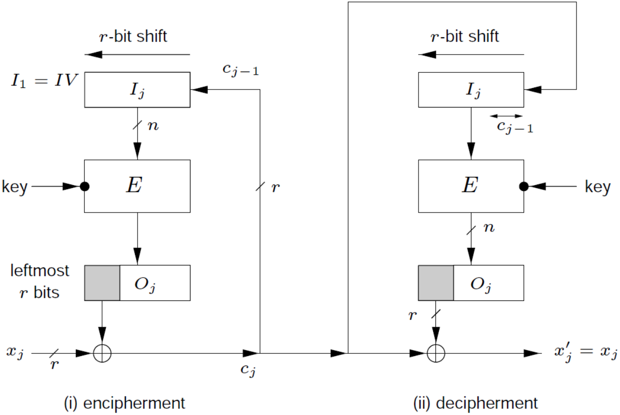

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DES

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- Main threat isn't cryptanalytic, but (slightly optimised) **exhaustive search** in small key-space. Remedied by **3DES** (triple DES), 3 keys:

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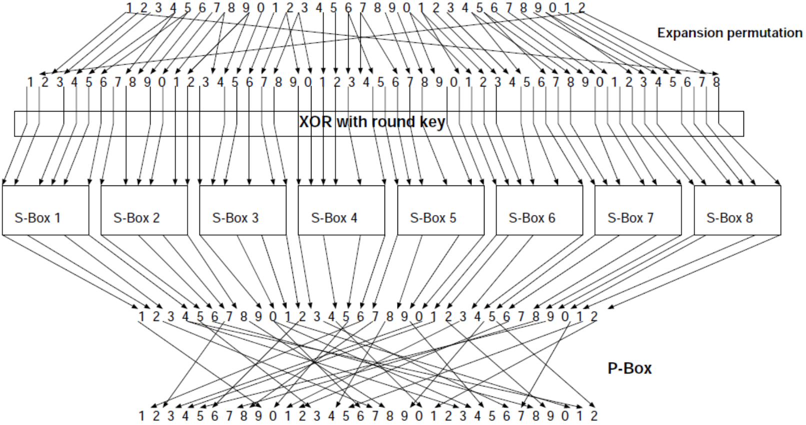
- Several other DES variants, including **DESX**, using *whitenening* keys k_1, k_2 as $C = E_k(P \oplus k_1) \oplus k_2$. (Used in Win2K encrypting FS).

Overview of DES internals [FIPS 46-3]



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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.