DES and AES

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Introduction

Objectives:

- Visit practical constructions of block ciphers.
- Apply concepts discussed in previous classes.

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- Apply concepts discussed in previous classes.

Hidden intentions:

- Observe how standardization processes can influence cryptographic design.

Feistel network

Definition

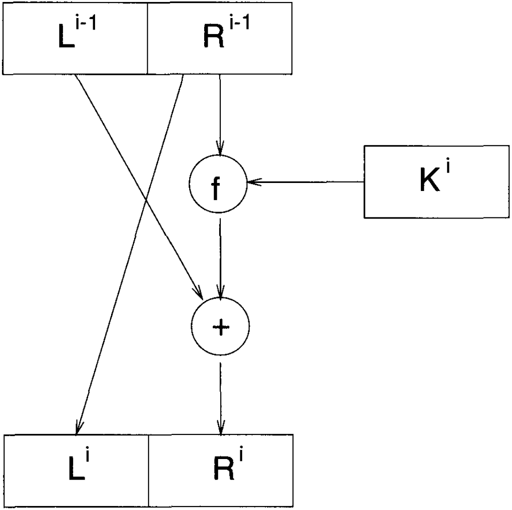
A **Feistel network** is a special case of iterated cipher where $g : \mathcal{M} \times \mathcal{K} \rightarrow \mathcal{C}$ has the form $g(L^{i-1}R^{i-1}, K^i) = (L^i R^i)$, where

$$L^i = R^{i-1}, R^i = L^{i-1} \oplus f(R^{i-1}, K^i).$$

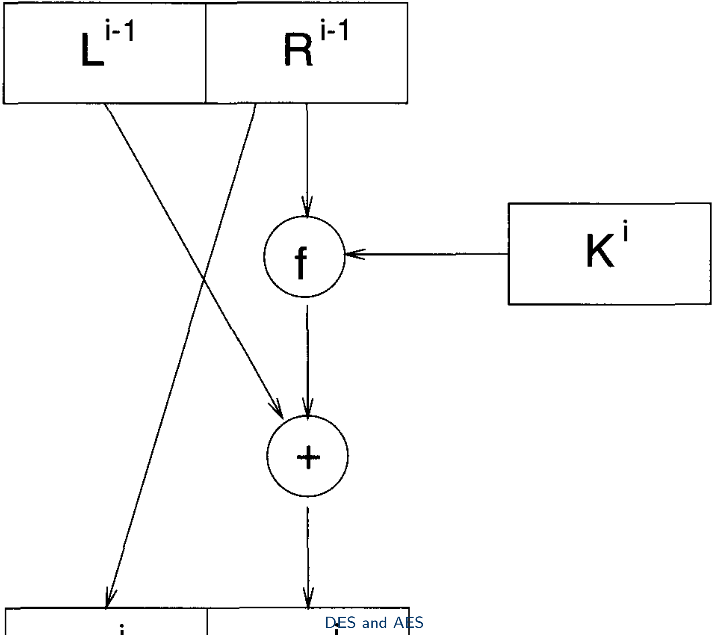
Characteristics:

- Cipher state w^i split into two halves L^i e R^i of the same size.
- There are no restrictions to function f, because g is invertible by definition.

Feistel network



Feistel network



Feistel network

Encryption algorithm

Input: $x, \pi, f_i, \langle K^1, K^2, \ldots, K^r \rangle$.

1 $L^0 \parallel R^0 \leftarrow x$

2 **for** $i \leftarrow 1$ **to** r **do**

  2.1 $L^i \leftarrow R^{i-1}$

  2.2 $R^i \leftarrow L^{i-1} \oplus f_i(K^i, R^{i-1})$ (compression!)

3 **return** $y \leftarrow L^r \parallel R^r$

Problem: if f_i is not invertible, how to decrypt?

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Solution: Round i can be inverted:

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Problem: if f_i is not invertible, how to decrypt?

Solution: Round i can be inverted:

$$R^{i-1} = L^i, L^{i-1} = R^i \oplus f_i(K^i, R^{i-1})$$

Data Encryption Standard (IBM, 1975)

History:

- Standard defined jointly by IBM and NSA (*National Security Agency*).
- Based on the *Lucifer* block cipher, designed by Feistel.
- It was proposed to have a lifetime of 10-15 years, but this was much longer in practice.

Important: NSA interference in the standardization effort?

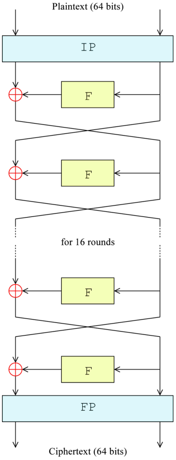
Data Encryption Standard (IBM, 1975)

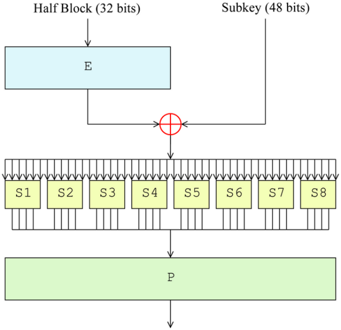
Features:

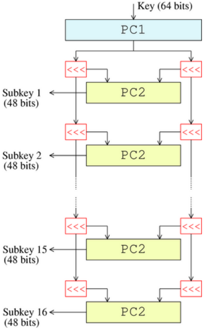
- $\mathcal{M} = (\mathbb{Z}_2)^{64}, \mathcal{K} = (\mathbb{Z}_2)^{56}$.
- 8-bit parity in the key.
- Permutation $L^0 R^0 = \boldsymbol{IP}(x)$ is applied at the beginning.
- Inverse permutation $y = \boldsymbol{IP}^{-1}(R^{16} L^{16})$ is applied at the end.
- $Nr = 16$, $lm = 64$.
- Function f has format $\{0,1\}^{32} \times \{0,1\}^{48} \rightarrow \{0,1\}^{32}$.
- Subkeys $(K^1, K^2, \ldots, K^{16})$ are permutations of the bits from K.

Question: Why is the purpose of $\boldsymbol{IP}$ e $\boldsymbol{IP}^{-1}$?

Data Encryption Standard (IBM, 1975)







Data Encryption Standard (IBM, 1975)

Analysis:

- Only the substitution boxes are non-linear.
- They are speculated to be vulnerable or to store a backdoor.
- They were actually chosen to resist differential cryptanalysis.
- 20 years later, researchers from academia independently discovered the attack.
- Any other problem?

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Analysis:

- Only the substitution boxes are non-linear.
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- They were actually chosen to resist differential cryptanalysis.
- 20 years later, researchers from academia independently discovered the attack.
- Small key space!

Data Encryption Standard (IBM, 1975)

Cryptanalysis:

- 1977: special-purpose machine costing 20 million was capable of brute-forcing the key space in a single day.
- CRYPTO 1993: special machine costing 100,000 capable of exhaustive search in $\frac{7}{2}$ of a day of a million in 1.5 day.
- 1994: Linear cryptanalsysis needs 2^{43} pairs (x, y).
- 1998: EFF builds *DES cracker* costing 250,000 and capable of exhaustive search in 56 hours.

Data Encryption Standard (IBM, 1975)

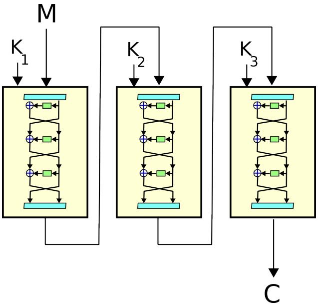
NSA wanted a secure cipher to everyone, but not *too* secure:

- Substitution boxes were chosen to improve resistance against differential cryptanalysis.
- Key length was reduced from 64 to 56 bits.

Conclusion: Never trust cryptographic standards to intelligence agencies (see DUAL_EC_DRBG and TLS export-grade cipher suites!)

Warning: Avoid DES at all costs, use AES!

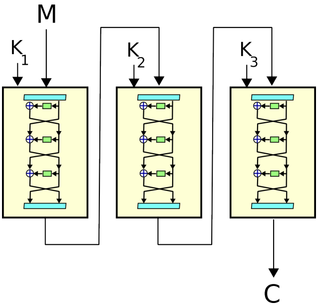
Triple DES



Encryption and decryption:

- $e_K(x) = e_{K_3}(d_{K_2}(e_{K_1}(x)))$
- $d_K(y) = d_{K_1}(e_{K_2}(d_{K_3}(y)))$

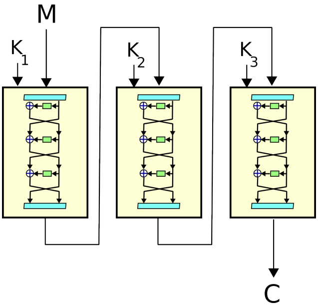
Triple DES



Variants:

- $K_1 = K_2 = K_3$ (56 bits of security).
- $K_1 = K_3 \neq K_2$ (112 bits of security).
- $K_1 \neq K_2 \neq K_3$ (168 bits of security).

Triple DES



Variants:

- $K_1 = K_2 = K_3$ (56 bits of security).
- $K_1 = K_3 \neq K_2$ (80 of security).
- $K_1 \neq K_2 \neq K_3$ (112 bits of security).

Meet-in-the-middle attack

Definition

It is a known-plaintext attack what exploits the naive intuition that double encryption with different keys is equivalent to encrypting with a key two times longer.

Assumptions:

- Encryption function is $e_K(x) = e_{K_1}(e_{K_2}(x))$.
- Decryption function is $d_K(y) = d_{K_2}(d_{K_1}(x))$.

Meet-in-the-middle attack

Algorithm

Input: Plaintext and ciphertext pair (x, y).
Output: Key K.

1. Attacker computes encryptions $y' = e_{K_1}(x)$ for all keys K_1.
2. Attacker stores all y' in a table.
3. Attacker computes decryptions $x' = d_{K_2}(y)$ for all keys K_2.
4. If $x' = y'$, attacker finds correct key $K = (K_1, K_2)$.

Important: What is the complexity?

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Important: 2^{n+1} encryptions and storage of 2^n ciphertexts!

Advanced Encryption Standard (2001, NIST)

History:

- Public challenge.
- 21 submissions, 15 accepted.
- 5 finalists: *MARS*, *RC6*, *Rijndael*, *Serpent* e *Twofish*.
- Cipher *Rijndael* selected as the standard.

Criteria:

- Security.
- Computational cost in software and hardware.
- Simplicity and flexibility in the design.

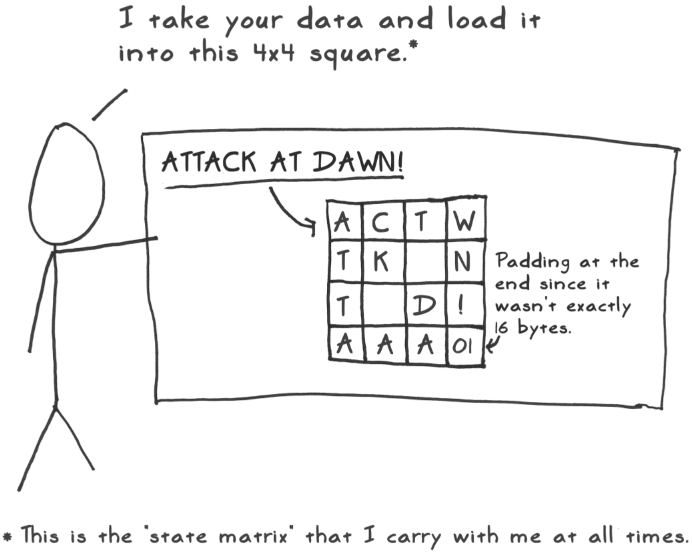
Advanced Encryption Standard (2001, NIST)

Features:

- Three security levels: 128, 192 e 256 bits.
- $\mathcal{M} = (\mathbb{Z}_2)^{128}, \mathcal{K} = (\mathbb{Z}_2)^{128}, (\mathbb{Z}_2)^{192}, (\mathbb{Z}_2)^{256}$.
- $Nr = 10, 12, 14$, respectively, $lm = 128$.
- Follows the SPN paradigm.

Curiosity: Implemented as native instruction in modern Intel processors!

Advanced Encryption Standard (2001, NIST)



Credit: Jeff Moser

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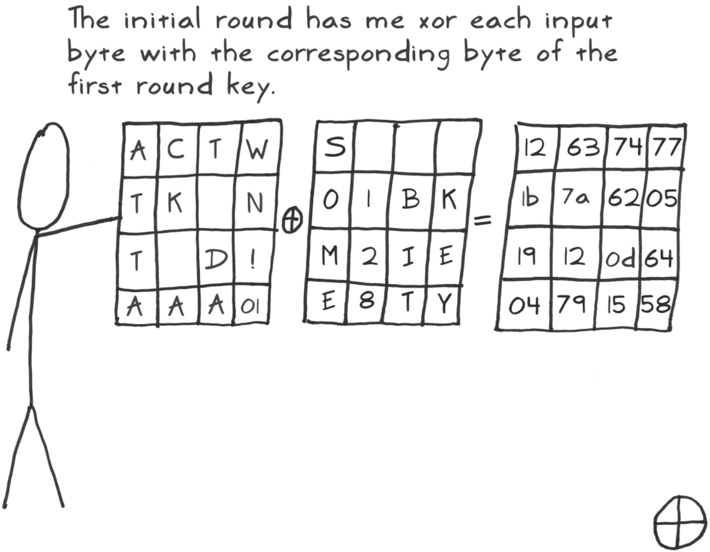

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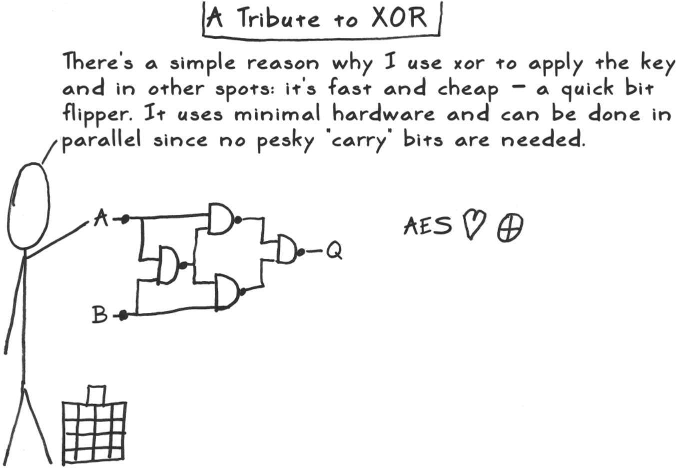

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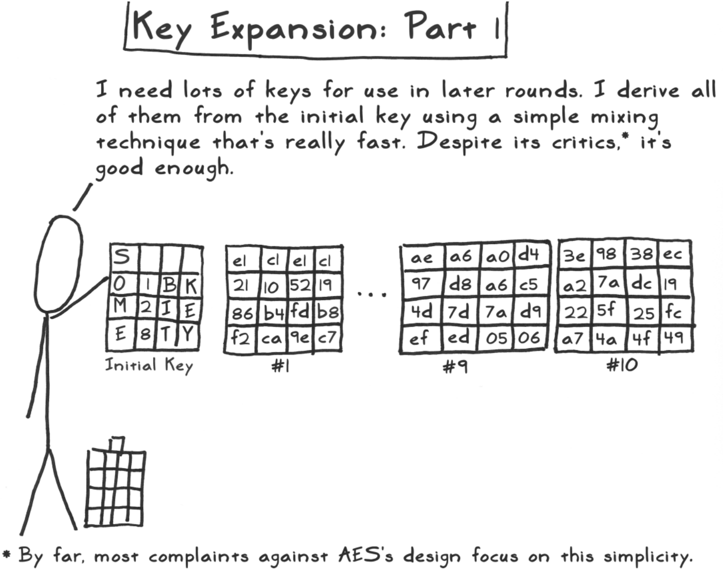

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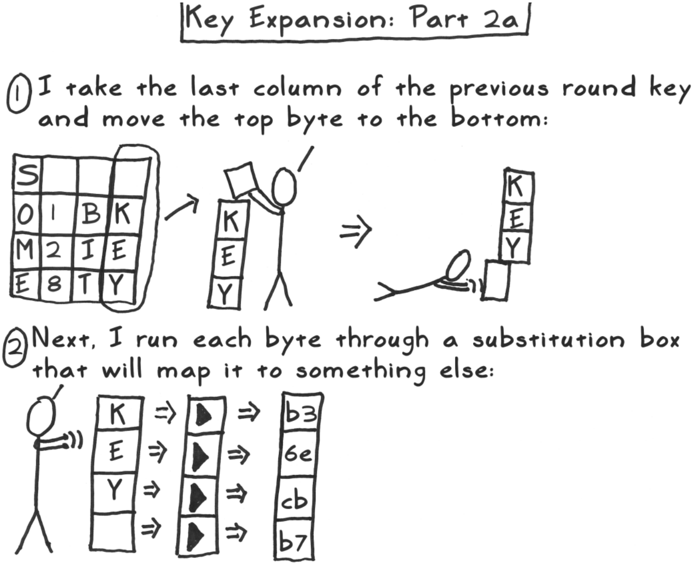

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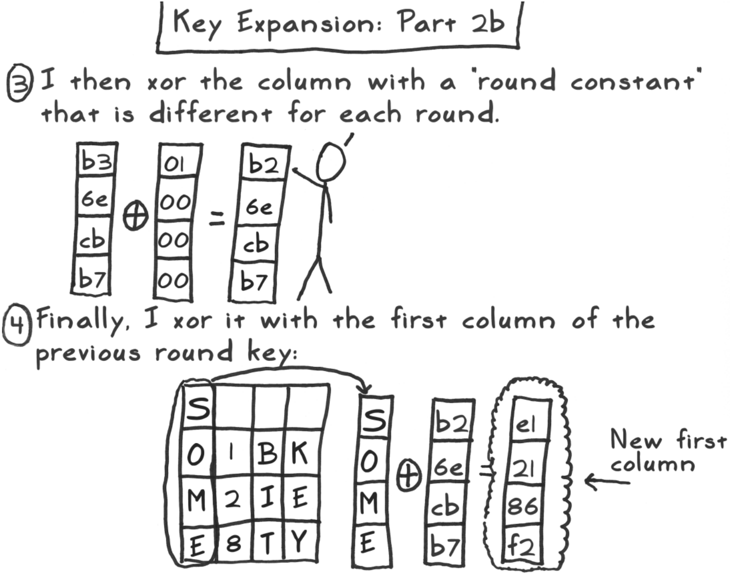

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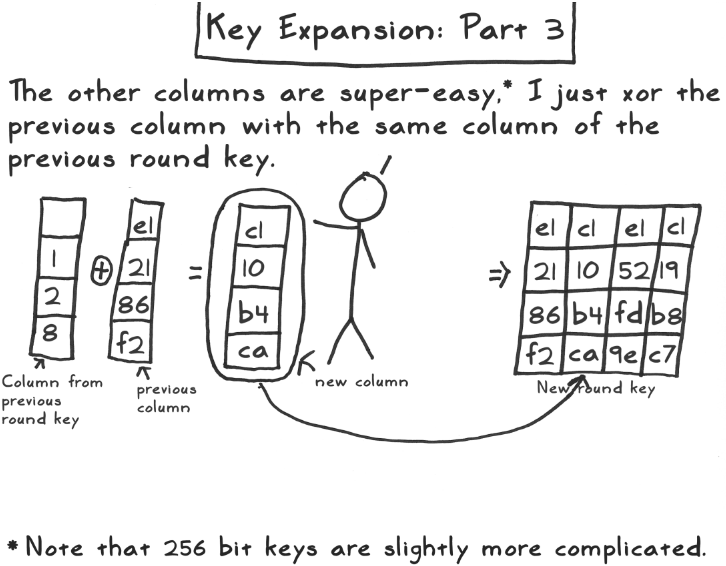

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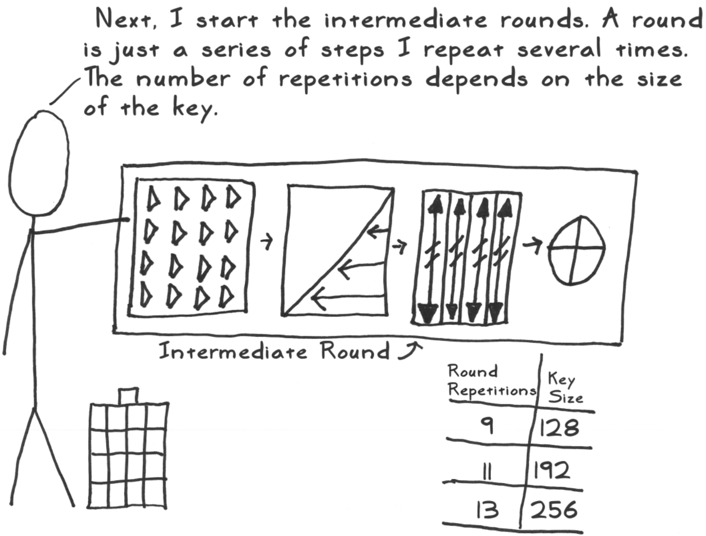

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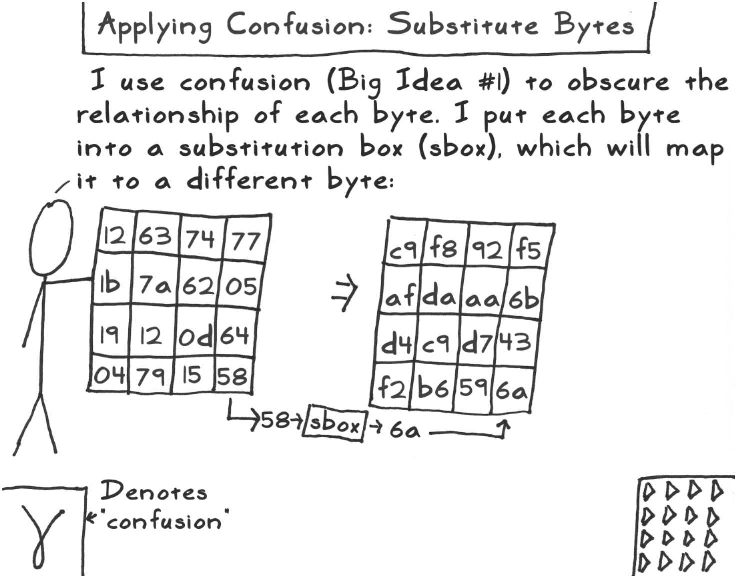

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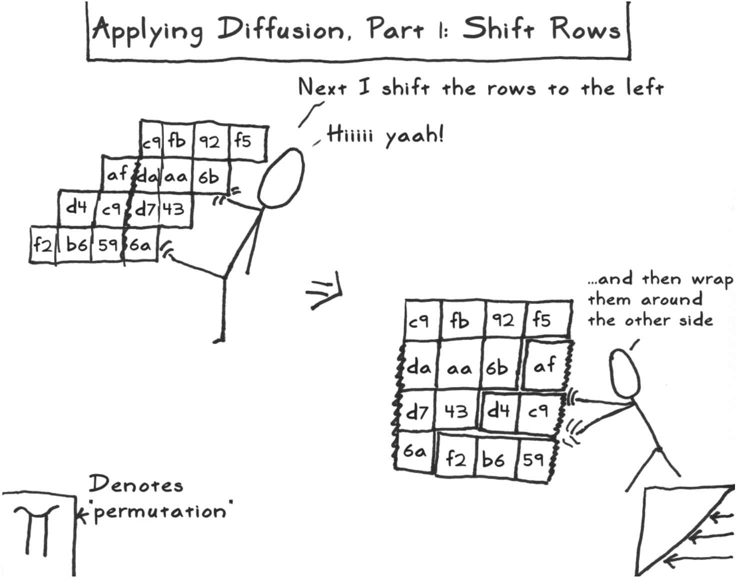

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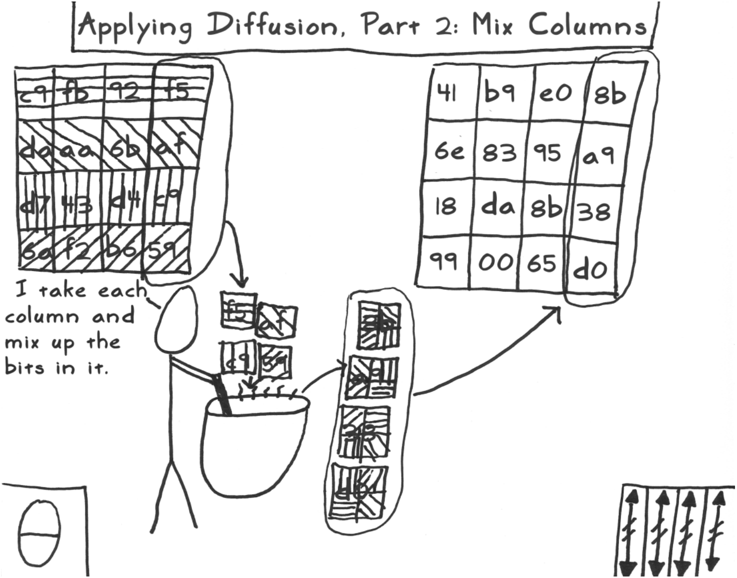

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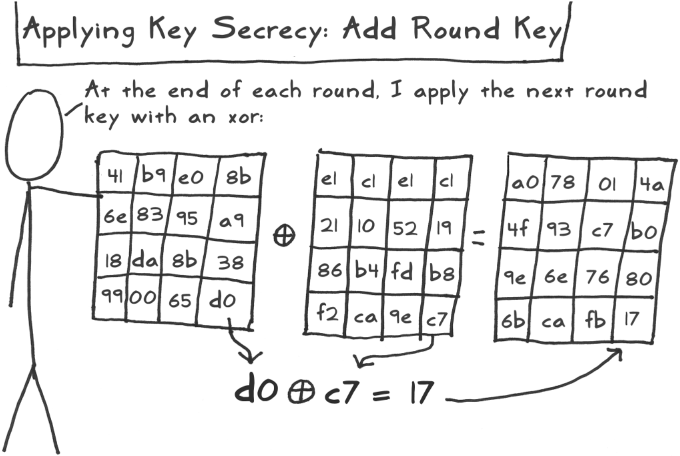

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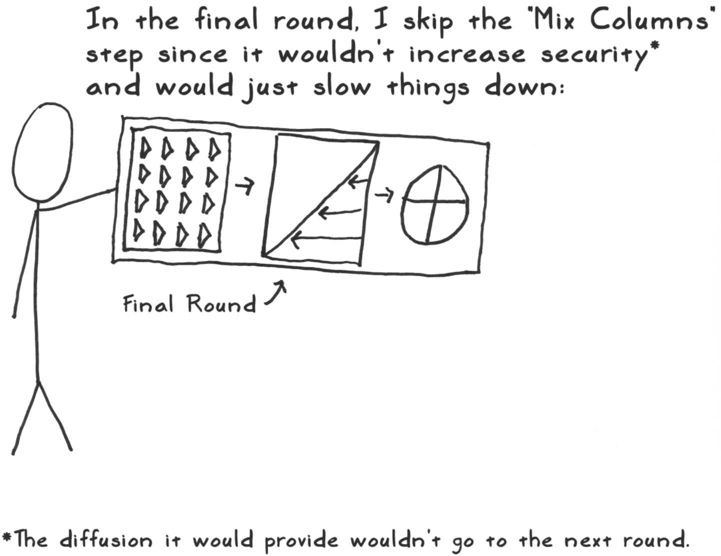

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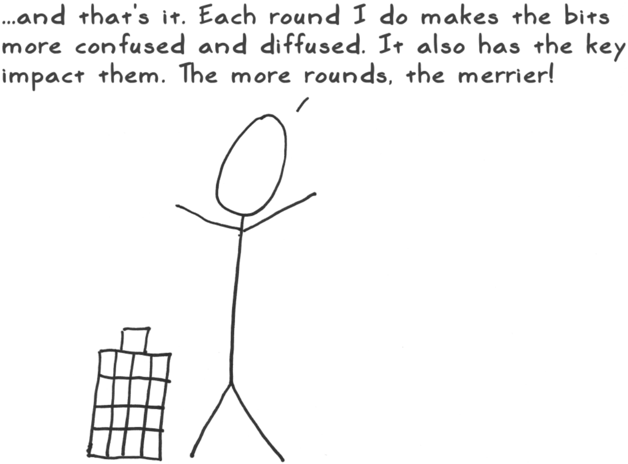

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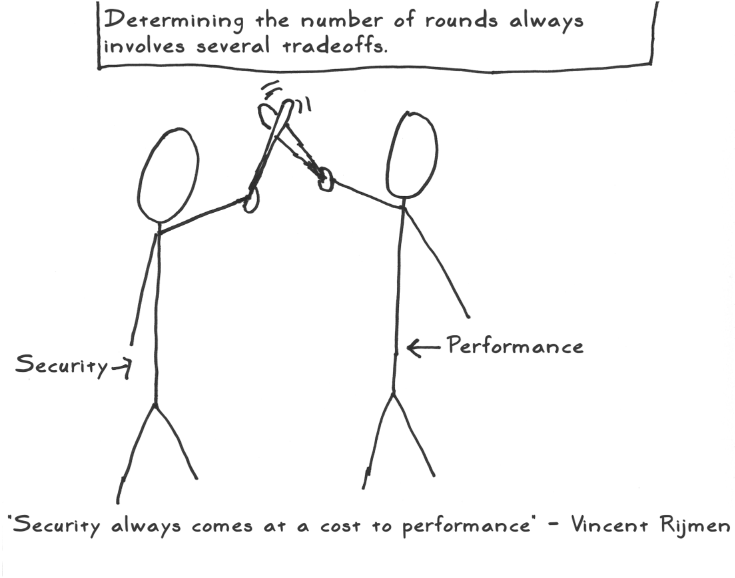

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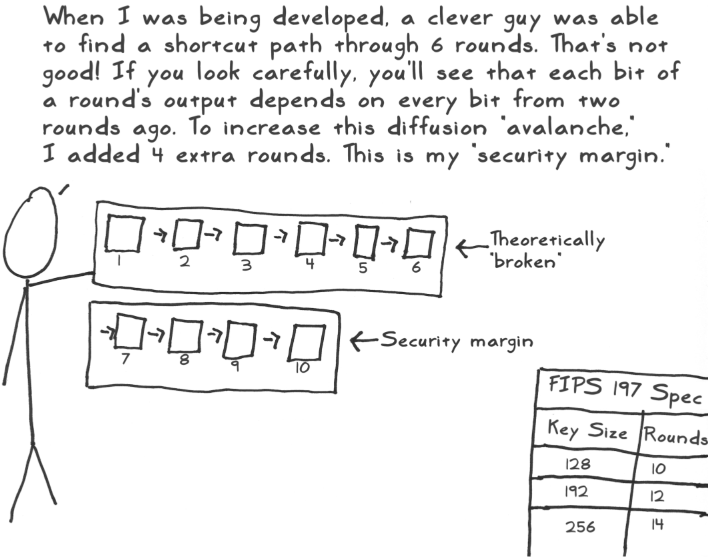

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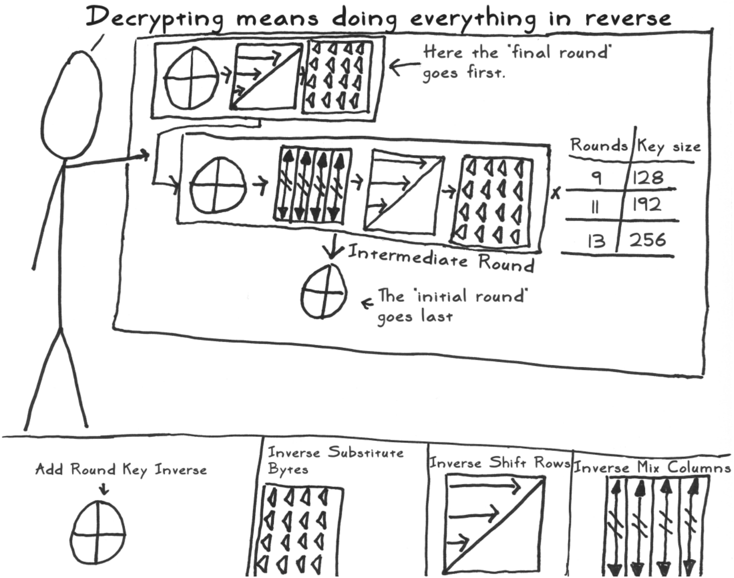

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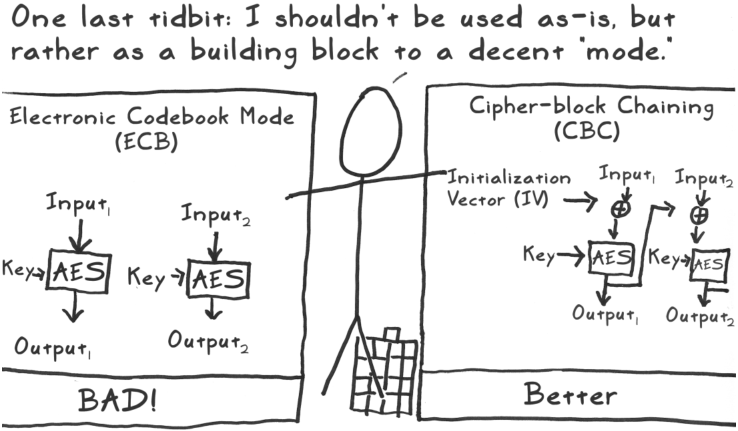

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