Constructing block ciphers: typically, relies on an "iterated cipher"

Difficult to design! Never invent your own crypto – use well-studied, standardized constructions and implementations!

We will look at two classic designs:

- DES / 3DES (Data Encryption Standard) 1977 (developed at IBM)
- AES (Advanced Encryption Standard) 2002 [most widely used block cipher, implemented in hardware in Intel processors]

on modern Intel processors, (with AES-NI), ~4 cycles/round

DES design uses 56-bit keys (and 64-bit blocks)

56-bit keys was a compromise between 40-bit keys (NIST/NSA) and 64-bit keys (cryptographers – notably Hellman)

↳ turned out to be insufficient

- 1997: DES challenge solved in 96 days (massive distributed effort)
- 1998: with dedicated hardware, DES can be broken in just 56 hours → not secure enough!
- 2007: using off-the-shelf FPGAs (120), can break DES in just 12.8 days → anyone can now break DES!

↳ 2-DES: apply DES twice (keys now 112-bits)

↳ meet-in-the-middle attack gives no advantage (though space usage is high)

↳ 3-DES: apply DES three times [$3DES((k_1,k_2,k_3),x) := DES(k_3, DES^{-1}(k_2, DES(k_1,x)))$]

↳ 168-bit keys – Standardized in 1998 after brute force attacks on DES shown to be feasible

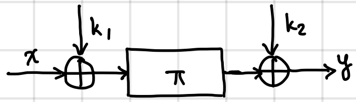
AES (2002 – most common block cipher in use today):

- 3DES is slow (3x slower than DES)
- 64-bit block size not ideal (recall that block size determines adversary's advantage when block cipher used for encryption)

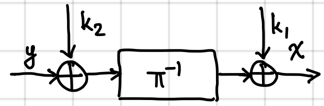
AES block cipher has 128-bit blocks (and 128-bit keys) also have 192-bit and 256-bit variants (but block size always 2^{128})

↳ follows another classic design paradigm: iterated Even-Mansour (also called alternating key ciphers)

Even-Mansour block cipher: keys (k_1, k_2), input x:



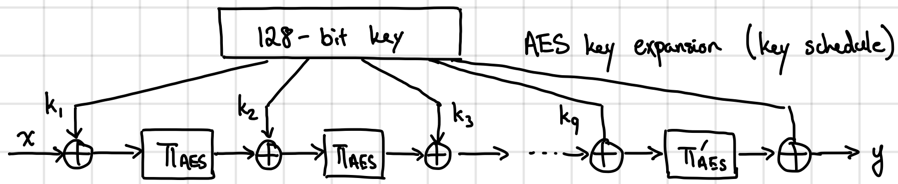
Evaluation



Inversion

<u>Theorem (Even-Mansour)</u>: If π is modeled as a random permutation, then the Even-Mansour block cipher is secure (i.e., it is a secure PRP).

The AES block cipher can be viewed as an iterated Even-Mansour cipher:



key-size
↓
- AES-128: 10 rounds
- AES-192: 12 rounds
- AES-256: 14 rounds

(block-size all 128 bits)

Permutations Π_{AES} and Π'_{AES} are fixed permutations and <u>cannot</u> be ideal permutations

↳ cannot write down random permutation over $\{0,1\}^{128}$

↳ Cannot appeal to security of Even-Mansour for security

↳ But still provides evidence that this design strategy is <u>viable</u> [similar to DES and Luby-Rackoff]

AES round permutation: composed of three invertible operations that each operate on a 128-bit block

a_0	a_1	a_2	a_3
a_4	a_5	a_6	a_7
a_8	a_9	a_{10}	a_{11}
a_{12}	a_{13}	a_{14}	a_{15}

128 bits arranged in 4-by-4 grid of bytes ($\{0,1\}^8$)

SubBytes: apply a <u>fixed</u> permutation $S: \{0,1\}^8 \to \{0,1\}^8$ to each cell

↳ hard coded in the AES standard (similar to S-box)
(chosen very carefully to resist attacks)

ShiftRows: cyclic shift the rows of the matrix
- 1st row unchanged
- 2nd row shifted left by 1
- 3rd row shifted left by 2
- 4th row shifted left by 3

MixColumns: the matrix is interpreted as a 4-by-4 matrix over $GF(2^8)$ and multiplied by a fixed <u>invertible</u> matrix (also carefully chosen and hard-coded into the standard)

elements are polynomials over $GF(2)$ ($\mathbb{F}_2$) modulo the irreducible polynomial $x^8 + x^4 + x^3 + x + 1$

<u>Observe</u>: Every operation is invertible, so composition is also invertible

Π_{AES} : SubBytes ; ShiftRows ; MixColumns

Π'_{AES} : SubBytes ; ShiftRows   No MixColumns for the last round [done so AES decryption circuit better resembles AES encryption]

<u>Security of AES</u>: Brute-force attack: 2^{128}

Best-known key recovery attack: $2^{126.1}$ time — only 4x better than brute force!

What does 2^{128}-time look like?

- Suppose we can try 2^{40} keys a second.
  - ↳ 2^{88} seconds to break 1 AES key $\sim 10^{19}$ years (710 million times larger than age of the universe!)
- Total computing power on Earth (circa 2015)
  - ↳ estimated to be $\sim 2^{70}$ operations/second (currently, bitcoin mining computes $\sim 2^{66}$ hashes/second)

Let's say we can do 2^{80} operations/second

↳ still require 2^{48} seconds to break AES $\sim$ 9 million years of compute

If we move to 256-bit keys, best brute force attack takes $2^{254.2}$ time (on AES-256)

e.g., quantum computers

In well-implemented systems, the cryptography is not the weak point — breaking the crypto requires new <u>algorithmic</u> techniques

↳ But side channels / bad implementations can compromise crypto