Network Security: Secret Key Cryptography

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Secret Key Cryptography

- fixed-size block, fixed-size key $\rightarrow$ block
- DES, IDEA
- message into blocks?

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Generic Block Encryption

- convert block into another, *one-to-one*
- long enough to avoid known-plaintext attack
- 64 bit typical (nice for RISC!) ➠ $18 \cdot 10^{18}$ (peta)
- naive: 2^{64} input values, 64 bits each $\rightarrow 2^{70}$ bits
- output should look random
- plain, ciphertext: no correlation (half the same, half different)
- ➠ bit spreading

substitution: $2^k, k \ll 64$ values mapped ➠ $k \cdot 2^k$ bits

permutation: change bit position of each bit ➠ $k \log_2 k$ bits to specify

round: combination of substitution of chunks and permutation
do often enough so that a bit can affect every output bit – but no more

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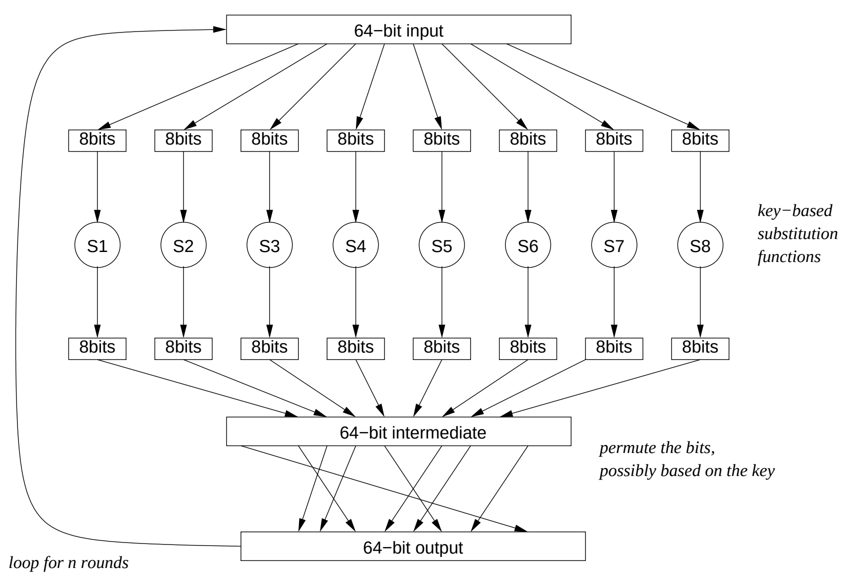
Block Encryption



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Data Encryption Standard (DES)

- published in 1977 by National Bureau of Standards
- developed at IBM (“Lucifer”)
- 56-bit key, with parity bits
- 64-bit blocks
- easy in hardware, slow in software
- 50 MIPS: 300 kB/s
- 10.7 Mb/s on a 90 MHz Pentium in 32-bit protected mode
- grow 1 bit every 2 years

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Breaking DES

- brute force: check all keys ➠ 500,000 MIPS years
- easy if you have known plaintext
- have to know something about plaintext (ASCII, GIF, . . .)
- commercial DES chips not helpful: key loading time $>$ decryption time
- easy to do with FPGA, without arousing suspicion
- easily defeated with repeated encryption

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DES Overview

- initial permutation
- 56-bit key $\rightarrow$ 16 48-bit per-round keys (different subset)
- 16 rounds: 64 bit input + 48-bit key $\rightarrow$ 64-bit output
- final permutation (inverse of initial)
- decryption: run backwards ➠ reverse key order

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Permutation

- just slow down software
- ith byte $\rightarrow (9 - i)$th bits
- even-numbered bits into byte 1-4
- odd-numbered bits into byte 5-8
- no security value: if we can decrypt innards, we could decrypt DES

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DES: Generating Per-Round Keys

56-bit key $\rightarrow$ 16 48-bit keys $K_1, \ldots K_{16}$:

- bits 8, 16, ..., 64 are parity
- permutation
- split into 28-bit pieces C_0, D_0: $57, 49, \ldots$
- again, no security value
- rounds 1, 2, 9, 16: single-bit rotate left
- otherwise: two-bit rotate left
- permutation for left/right half of K_i
- discard a few bits ➠ 48-bit key in each round

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XOR Arithmetic

- $x \oplus x = 0$
- $x \oplus 0 = x$
- $x \oplus 1 = \bar{x}$

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DES Round

- mangler function can be non-reversible
  - $L_{n+1} = R_n$
  - $R_{n+1} = m(R_n, K_n) \oplus L_n$
- decryption
  - $R_n = L_{n+1}$
  - $L_n = m(R_n, K_n) \oplus R_{n+1}$

because ($\oplus L_n, R_{n+1}$): $R_{n+1} \oplus R_{n+1} \oplus L_n = m() \oplus L_n \oplus L_n \oplus R_{n+1}$

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DES Mangler Function

- $R(32), K(48) \oplus L_n \rightarrow R_{n+1}$
- expand from 32 to 48 bits: 4-bit chunks, borrow bits from neighbors
- 6-bit chunks: expanded $R \oplus K$
- 8 different S-boxes for each 6 bits of data
- **S box**: 6 bit (64 entries) into 4 bit (16) table: 4 each
- four separate 4x4 S-boxes, selected by outer 2 bits of 6-bit chunk
- afterwards, random permutation: P-box

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DES: Weak Keys

- 16 keys to avoid: C_0, D_0 0…0, 1…1, 0101…, 1010…
- sequential key search ➠ avoid low-numbered keys
- 4 *weak keys* = $C_0, D_0 = 0 \ldots 0$ or $1 \ldots 1$ ➠ own inverses: $E_k(m) = D_k(m)$
- semi-weak keys: $E_{k_1}(m) = D_{k_2}(m)$

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IDEA

- International Data Encryption Algorithm
- ETH Zurich, 1991
- similar to DES: 64 bit blocks
- but 128-bit keys

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Primitive Operations

2 16-bit $\to$ 1 16-bit:

- $\oplus$
- $+ \bmod 2^{16}$
- $\otimes \bmod 2^{16} + 1$:
  - reversible ➠ $\exists$ inverse y of x, $\forall x \in [1, 2^{16}] a \otimes x \otimes y = a$
  - or $x \otimes y = 1$
  - example: $x = 2, y = 32769$ ➠ Euclid's algorithm
  - reason: $2^{16} + 1$ is prime
  - treat 0 as encoding for 2^{16}

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IDEA Key Expansion

- 128-bit key $\to$ 52 16-bit keys $K_1, \ldots, K_{52}$
- encryption, decryption: different keys
- key generation:
  - first chop off 16 bit chunks from 128 bit key ➠ eight 16-bit keys
  - start at bit 25, chop again ➠ eight 16-bit keys
  - shift 25 bits and repeat

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IDEA: One Round

- 17 rounds, even and odd
- 64 bit input $\rightarrow$ 4 16-bit inputs: X_a, X_b, X_c, X_d
- operations $\rightarrow$ output X'_a, X'_b, X'_c, X'_d
- odd rounds use $4K_i : K_a, K_b, K_c, K_d$
- even rounds use $2K_i : K_e, K_f$

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IDEA: Odd Round

- $X'_a = X_a \otimes K_a$
- $X'_d = X_d \otimes K_d$
- $X'_c = X_b + K_b$
- $X'_b = X_c + K_c$

reverse with inverses of K_i:
$X'_a \otimes K'_a = X_a \otimes K_a \otimes K'_a$

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IDEA: Even Round

mangler: $Y_{\text{out}}, Z_{\text{out}} = f(Y_{\text{in}}, Z_{\text{in}}, K_e, K_f)$

1.
$$\begin{aligned} Y_{\text{in}} &= X_a \oplus X_b \\ Z_{\text{in}} &= X_c \oplus X_d \end{aligned}$$

2.
$$\begin{aligned} Y_{\text{out}} &= ((K_e \otimes Y_{\text{in}} + Z_{\text{in}}) \otimes K_f \\ Z_{\text{out}} &= K_e \otimes Y_{\text{in}} + Y_{\text{out}} \end{aligned}$$

3.
$$\begin{aligned} X'_a &= X_a \oplus Y_{\text{out}} \\ X'_b &= X_b \oplus Y_{\text{out}} \\ X'_c &= X_c \oplus Z_{\text{out}} \\ X'_d &= X_d \oplus Z_{\text{out}} \end{aligned}$$

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IDEA Even Round: Inverse

$$X'_a = X_a \oplus Y_{\text{out}}$$

Feed X'_a to input:

$$\begin{aligned} &= X'_a \oplus Y_{\text{out}} \\ &= (X_a \oplus Y_{\text{out}}) \oplus Y_{\text{out}} \\ &= X_a \end{aligned}$$

➠ round is its own inverse! ➠ same keys

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Encrypting a Large Message

- Electronic Code Book $\boxed{\text{(ECB)}}$
- Cipher Block Chaining $\boxed{\text{(CBC)}}$
- k-bit Cipher Feedback Mode (CFB)
- k-bit Output Feedback Mode (OFB)

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Electronic Code Book (ECB)

- break into 64-bit blocks
- encrypt each block independently
- some plaintext ➠ same ciphertext
- easy to change message by copying blocks
- bit errors do not propagate

➠ rarely used

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Cipher Block Chaining (CBC)

simple fix: $\oplus$ blocks with 64-bit random number

- must keep random number secret
- repeats in plaintext $\not\to$ = ciphertext
- can still remove selected blocks

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Cipher Block Chaining (CBC)

- random number $r_{i+1} = c_i$: previous block of ciphertext
- random (but public) *initialization vector* (IV): avoid equal initial text
- Trudy can't detect changes in plaintext
- can't feed chosen plaintext to encryption
- but: can twiddle some bits (while modifying others): modify c_n to change desired m_{n+1} (and m_n)
- ➠ combine with MICs

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Output Feedback Mode (OFB)

64-bit OFB:

- IV: $b_0 \stackrel{\text{encrypt}}{\longrightarrow} b_1 \stackrel{\text{encrypt}}{\longrightarrow} b_2 \ldots$
- $c_i = m_i \oplus b_i$, transmit with IV
- ciphertext damage ➠ limited plaintext damage
- can be transmitted byte-by-byte
- but: known plaintext ➠ modify plaintext into anything
- extra/missing characters garble whole rest

variation: k-bit OFB

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Cipher Feedback Mode (CFB)

- similar to OFB: generate k bits, $\oplus$ with plaintext
- use k bits of *ciphertext* instead of IV-generated
- ➠ can't generate ahead of time
- 8-bit CFB will resynchronize after byte loss/insertion
- requires encryption for each k bits

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Generating MICs

- only send last block of CBC ➠ *CBC residue*
- any modification in plaintext modifies CBC residue
- replicating last CBC block doesn't work
- P+I: use separate (but maybe related) secret keys for encryption and MIC ➠ two encryption passes
- CBC(message | hash)

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Multiple Encryption DES

- applicable to any encryption, important for DES
- encrypt-decrypt-encrypt (EDE): just reversible *functions*
- two keys K_1, K_2

$$\begin{array}{ccccccccc} & & K_1 & & K_2 & & K_1 & & \\ & & \downarrow & & \downarrow & & \downarrow & & \\ m & \rightarrow & E & \rightarrow & D & \rightarrow & E & \rightarrow & c \end{array}$$

- decryption ➠ just reverse:

$$\begin{array}{ccccccccc} & & K_1 & & K_2 & & K_1 & & \\ & & \downarrow & & \downarrow & & \downarrow & & \\ c & \rightarrow & D & \rightarrow & E & \rightarrow & D & \rightarrow & m \end{array}$$

- standard CBC

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Triple DES: Why 3?

- security $\leftrightarrow$ efficiency
- $K_1 = K_2$: twice the work for encryption, cryptanalyst
- plaintext $m_i \xrightarrow{A:E(K_1)} r \xrightarrow{B:E(K_2)} c_i$ (ciphertext)
- *not* quite equivalent to 112 bit key:
  - assume given $(m_1, c_1), (m_2, c_2), (m_3, c_3)$
  - Table A: 2^{56} (10^4 TB) entries: $r = K\{m_1\}\forall K$, sort by r
  - Table B: 2^{56} entries: $r = c_1$ decrypted with K, sorted
  - find matching r ➠ K_A, K_B
  - if multiple K_A, K_B pairs, test against m_2, c_2, etc.
  - 2^{64} values, 2^{56} entries ➠ 1/256 chance to appear in table ➠ 2^{48} matches

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Triple DES: Why 3?

Table A:

$r = E(m_1, K)$ (64 bits)	K (56 bits)
...	
1234567890abcd00	ab485095845922
1234567890abcd03	12834893573257
1234567890abcd04	43892ab8348a85
1234567890abcd08	185ab80184092c
...	

Table B:

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$r = D(c_1, K)$ (64 bits)	K (56 bits)
$\ldots$	
1234567890abcd00	38acd043858ac0
1234567890abcd03	91870ab8a8d8a0
1234567890abcd07	058a0fa858abcd
1234567890abcd09	fd884a90407821
$\ldots$	

computation: $2 \cdot 2^{56} + 2^{48}$

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Triple DES

- EDE: can run as single DES with $K_1 = K_2$
- can be used with any chaining method
- CBC on the outside ➠ no change in properties
- CBC on the inside ➠ avoid plaintext manipulation
- but want *self-synchronizing*: wrong bit x in block $n-1$ ➠ $n-1$ garbled, n_x changed, others unaffected
- CBC inside: parallelization

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