# Protezione e Sicurezza nei Sistemi Operativi:
# A (Brief) History of Cryptography

*Ozalp Babaoglu*

ALMA MATER STUDIORUM – UNIVERSITA' DI BOLOGNA

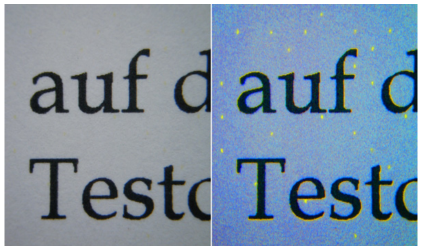
## Steganography

- From the Greek ***steganós*** (στεγανός) — "covered", "concealed", and — ***graphein*** (γραφή) — "writing"
- The art of concealing information within other information
- Form of "security through obscurity"
- Can be made "keyless"
- Real world examples:
  - Message written in secret ink on paper
  - Message written on the scalp of messenger



## Steganography

- Different steganography techniques depending on the type of "container" object:
  - Text steganography
  - Image steganography
  - Audio steganography
  - Video steganography
  - Network steganography
  - Printer steganography





## Caesar Cipher

- A *substitution* cipher
- Each letter of the plaintext is replaced by a unique letter in the ciphertext
- Which letter?
- In the case of Caesar Cipher, the relation between the letter in the plaintext and that in the ciphertext is obtained through a ***cyclic left shift***
- Decryption is obtained through a ***cyclic right shift***
- Example: shift 3

```
   abcdefghijklmnopqrstuvwxyz
C                              D
   ABCDEFGHIJKLMNOPQRSTUVWXYZ
```

## Caesar Cipher

```
ignavi coram morte quidem animam trahunt,
audaces autem illam non saltem advertunt
LJQDYLCFRUDPCPRUWHCTXLGHPCDQLPDPCWUDKXQWCCDX
GDFHVCDXWHPCLOODPCQRQCVDOWHPCDGYHUWXQW
```

- Number of positions to shift becomes the secret key of the cipher
- Let $pos(\alpha)$ be the position of letter $\alpha$ in the alphabet,
- Let $chr(j)$ be the character in the $j$-th position of the alphabet,
- Let $k$ be the key,
- Let $m_i$ and $c_i$ the $i$-th characters in the plaintext and ciphertext, respectively

$C(m_i) = chr\,(pos(m_i) + k)$ **mod** 26

$D(c_i) = chr\,(pos(c_i) - k)$ **mod** 26



## Caesar Cipher

- Trivial to carry out a brute-force attack because:
  - The encryption and decryption algorithms are known
  - The number of possible keys is very small (only 25 different keys)
  - The language of the plaintext is known and easily recognizable
- Example: Cryptanalysis of

"`AJSN ANIN ANHN`"



## Caesar Cipher

- Brute-force cryptanalysis of ciphertext "`AJSN ANIN ANHN`"

```
Caesar(1) = zirm zmhm zmgm
Caesar(2) = yhql ylgl ylfl
Caesar(3) = xgpk xkfk xkek
Caesar(4) = wfoj wjej wjdj
Caesar(5) = veni vidi vici
Caesar(6) = udmh uhch uhbh
Caesar(7) = tclg tgbg tgag
Caesar(8) = sbkf sfaf sfzf
Caesar(9) = raje reze reye
Caesar(10) = qzid qdyd qdxd
…
```



## Substitution Ciphers

- Instead of substituting letters through a cyclic shift, we can substitute them through a *permutation* of the alphabet, which becomes the key:

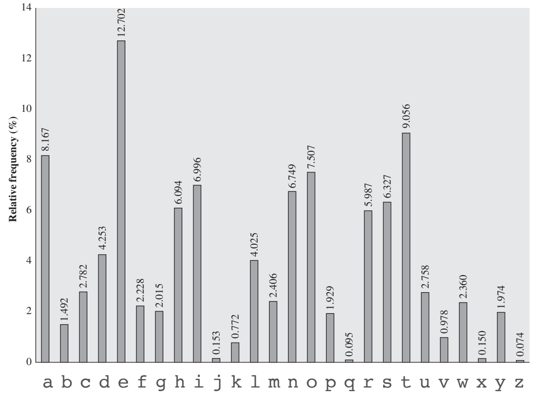
```
abcdefghijklmnopqrstuvwxyz

BFRULMZQWJEASOVKHXPGDTIYCN
```

- For an alphabet of 26 letters, there are 26! possible keys since there are 26! possible permutations of 26 letters
- Cryptanalysis through "brute force" becomes non practical
- However, ***statistical*** cryptanalysis is still possible

## Substitution Ciphers

- Relative frequency of letters in English text






## Substitution Ciphers

- Consider the ciphertext

```
UZQSOVUOHXMOPVGPOZPEVSGZWSZOPFPESXUDBMETSXAIZ
VUEPHZHMDZSHZOWSFPAPPDTSVPQUZWYMXUZUHSX
EPYEPOPDZSZUFPOMBZWPFUPZHMDJUDTMOHMQ
```

- Frequency of the letters in the ciphertext

| | | | | |
|---|---|---|---|---|
| P 13.33 | H 5.83 | F 3.33 | B 1.67 | C 0.00 |
| Z 11.67 | D 5.00 | W 3.33 | G 1.67 | K 0.00 |
| S 8.33 | E 5.00 | Q 2.50 | Y 1.67 | L 0.00 |
| U 8.33 | V 4.17 | T 2.50 | I 0.83 | N 0.00 |
| O 7.50 | X 4.17 | A 1.67 | J 0.83 | R 0.00 |
| M 6.67 | | | | |



## Substitution Ciphers

- The two most-frequent cipher letters `P` and `Z` probably correspond to the two most-frequent plain letters `e` and `t`
- Cipher letters `S,U,O,M,H,D` probably correspond to plain letters `a,o,i,n,s,h`
- The least frequent cipher letters `A,B,G,Y,I,J` probably correspond to the least frequent plain letters `v,k,j,x,q,z`



## Substitution Ciphers

- To resolve ambiguities, we can look at two-letter combinations
- In ciphertext, the most common 2-letter sequence is `ZW`
- In English language texts, the most common 2-letter sequence is `th`
- So, `Z` is most likely `t` and `W` is `h` meaning `P` is `e`
- Thus, the sequence `ZWP` in the ciphertext is probably `the`

## Polyalfabetic Ciphers

- Use multiple substitution ciphers depending on the position of the letter in the plaintext

```
     abcdefghijklmno...
a    ABCDEFGHIJKLMNO..
b    BCDEFGHIJKLMNO...
c    CDEFGHIJKLMNO...
d    DEFGHIJKLMNO...
...        ...
y    YZABCDEFGHIJK...
z    ZABCDEFGHIJ...
```

| | |
|---|---|
| key $k$ | gcaigcaigcai... |
| plaintext | dadybeca... |
| ciphertext | JCDGHGCI... |

- Monoalfabetic for every $|k|$ characters
- Statistical attack still possible but becomes more difficult
- Basis for “rotor machines” like *Enigma* and *Purple* that were used during world war 2



## Secret-Key Cryptography
## Polyalfabetic Ciphers

- Instead of substituting single letters of the plaintext, substitute blocks of letters
- Example (blocks of 3)
  - AAA → SOM
  - AAB → PLW
  - ABA → RTQ
  - ABB → SLL
  - …
- Doing so hides information regarding the frequency of single letters and pairs of letters



## Secret-Key Cryptography
## Permutation Ciphers

- Maintain the same letters in the ciphertext as in the plaintext, but change their order
- For example,

```
4312567   key
attackp
ostpone   plaintext
duntilt
hreepmx
```

Ciphertext: ttne apte tsur aodh coip knlm petx



## Secret-Key Cryptography
## Permutation Ciphers

- Can be repeated multiple times

```
4312567   key
ttneapt
etsurao   plaintext
dhcoipk
nlmpetx
```

output: nscmeuoptthltednariepapttokx

## Secret-Key Cryptography
## Permutation Ciphers

01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28

After one permutation:

03 10 17 24 04 11 18 25 02 09 16 23 01 08 15 22 05 12 19 26 06 13 20 27 07 14 21 28

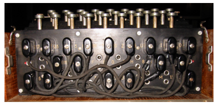
After two permutations:

17 09 05 27 24 16 12 07 10 02 22 20 03 25 15 13 04 23 19 14 11 01 26 21 18 08 06 28



## Enigma

Portable electro-mechanical device invented after WW I and used extensively by Germany to encode and decode messages exchanged with troops and with U-Boats during WW II

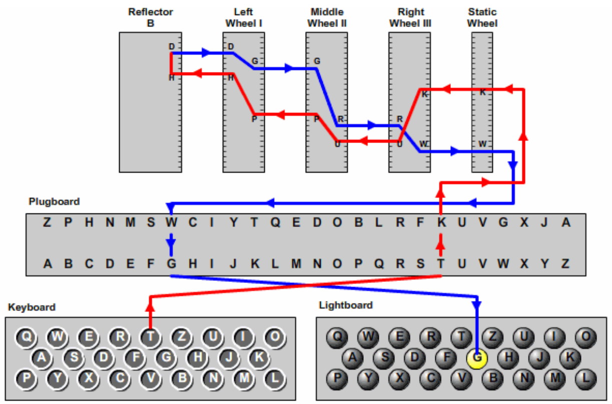


Plugboard: wired to correspond to a specific initial substitution

3 Rotors initialized to a specific setting, one or more rotors "step" with each key press



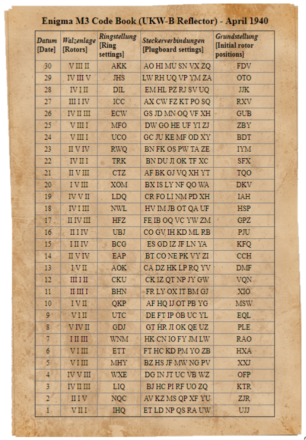
## How Enigma Worked






## How Enigma Worked

- "Code Book" contains the settings to be used for each day of the month
- Written in soluble ink so that if a submarine sank, the book would self-destruct

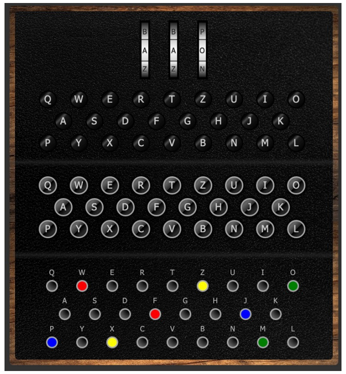


Enigma M3 Code Book (UKW-B Reflector) - April 1940

| *Datum* [Date] | *Walzenlage* [Rotors] | *Ringstellung* [Ring settings] | *Steckerverbindungen* [Plugboard settings] | *Grundstellung* [Initial rotor positions] |
|---|---|---|---|---|
| 30 | V III II | AKK | AO HI MU SN VX ZQ | FDV |
| 29 | IV III V | JHS | LW RH UQ VP YM ZA | OTO |
| 28 | IV I II | DIL | EM HL PZ RJ SV UQ | JJK |
| 27 | III I IV | ICC | AX CW FZ KT PO SQ | RXV |
| 26 | IV II III | ECW | GS JD MN OQ VF XH | GUB |
| 25 | V III I | MFO | DW GO HE UF YI ZJ | ZBY |
| 24 | V III I | UCO | GC JU KE MF OD XY | BDT |
| 23 | II V IV | RWQ | BN FK OS PW TA ZE | IYM |
| 22 | IV II I | TRK | BN DU JI OK TF XC | SFX |
| 21 | II V III | CTZ | AF BK GJ VQ XH YT | TQO |
| 20 | I V III | XOM | BX IS LY NF QO WA | DKV |
| 19 | IV V II | LDQ | CR FO LI NM PD XH | IAH |
| 18 | IV I III | NWL | HV IM JB OT QA UF | HSP |
| 17 | II IV III | HFZ | FE IB OQ VC YW ZM | GPZ |
| 16 | II I IV | UBJ | CO GV IH KD ML RB | PJU |
| 15 | I II IV | BCG | ES GD IZ JF LN YA | KFQ |
| 14 | II V IV | EAP | BT CO NE PK VY ZI | CCH |
| 13 | I V II | AOK | CA DZ HK LP RQ YV | DMF |
| 12 | III I II | CKU | CK IZ QT NP JY GW | VQN |
| 11 | II III I | BHN | FR LY OX IT BM GJ | XIO |
| 10 | I V II | QKP | AF HQ IJ OT PB YG | MSW |
| 9 | V I II | UTC | DE FT IP OB UC YL | EQL |
| 8 | V IV II | GDJ | GT HR JI OK QE UZ | PLE |
| 7 | I II III | WNM | HK CN IO FY JM LW | RAO |
| 6 | V I III | ETT | FT HC KD PM YO ZB | HXA |
| 5 | V I III | MHY | BZ HS JF MW NG PV | XXJ |
| 4 | IV V III | WXE | DG IN JT UC VB WZ | OFP |
| 3 | IV II III | LIQ | BJ HC PI RF UO ZQ | KTR |
| 2 | II I V | NQC | AV KZ MS QP XF YU | ZJR |
| 1 | V II I | IHQ | ET LD NP QS RA UW | UJJ |

## How Enigma Worked

- Enigma Machine Emulator





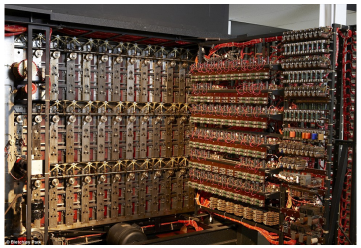

## Breaking Enigma

- The plugboard and the rotors define the “key” with 158,962,555,217,826,360,000 (~$10^{21}$) possible settings
- By the early 1940’s, a team of British cryptologists led by Alan Turing assembled at Bletchley Park, Buckinghamshire UK were able to decode thousands of intercepted messages per day
- Relied on earlier work by Polish cryptologists, Marian Rejewski, Jerzy Różycki and Henryk Zygalski
- Fundamental weakness of Enigma was the fact that no letter ever mapped to itself
- This weakness could be exploited in “known plaintext attacks”
- The Germans always started their daily transmission with a weather report and ended it with “Heil Hitler””



## Breaking Enigma

- The British and the US Navy built electro-mechanical devices called “Bombes” to speed their search of the key space by eliminating incorrect guesses
- Breaking Enigma is widely considered to have been decisive to the Allied victory of WW2





# “Perfect” Ciphers: One-Time Pad

## One-time pad

- *Symmetric* cipher that achieves "perfect computational" secrecy
- *Stream* cipher in that each bit of the ciphertext is determined solely by the corresponding bit of the plaintext and the key
- Based on random strings and modular arithmetic operations
- More of a theoretical concept than a practical solution



## One-time pad: example

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Plaintext: | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | |
| Key (Pad): | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | |
| $\oplus$ | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | Ciphertext |
| $\oplus$ | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | Plaintext |

Based on modular arithmetic:
$c_i = m_i + k_i$ **mod** 2 (also called "exclusive or")
For textual messages: $c_i = m_i + k_i$ **mod** 26



## Advantages and Defects

- Advantages:
  - Since each bit of the key is generated at random, knowing one bit of the ciphertext does not provide any information beyond guessing regarding the corresponding bit of the plaintext: guarantees *computational secrecy*
- Defects:
  - The key is as long as the plaintext message,
  - Self destructs (one-time),
  - Needs to be agreed upon



# DES
# Data Encryption Standard

## History

- In 1973, the ***National Bureau of Standards*** (now called the ***National Institute of Standards and Technology***) publishes a “call for proposals”
- IBM submits a proposal for a system similar to an internal product called “Lucifer”
- Soon after, the ***National Security Agency*** (NSA) adopts Lucifer under the name DES
- After further studies, DES is certified and made public in 1977
- First example of a robust cipher (with NSA certification) that the research community can study
- Thereafter certified every 5 years



## Characteristics of DES

- Symmetric cipher (secret-key cryptography)
- Works in 64-bit *blocks* (*not* a stream cipher)
- 64-bit keys, of which only 56 bits are used (other 8 serve as parity checks)

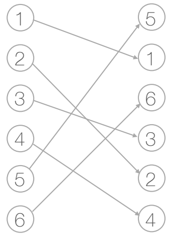


## Basic Operations

- Permutation
- Substitution
- Expansion
- Choice (contraction)
- Circular shift (left or right)



## Permutation




P=(5,1,6,3,2,4)

One bit of input determines one bit of output

## Substitution

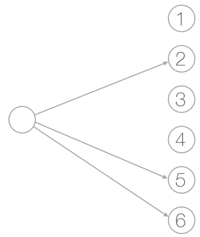
- Block of input bits replaced by a unique block of output bits

| | |
|---|---|
| 000 | 010 |
| 001 | 011 |
| 010 | 100 |
| 011 | 111 |
| 100 | 110 |
| 101 | 000 |
| 110 | 001 |
| 111 | 101 |



## Expansion

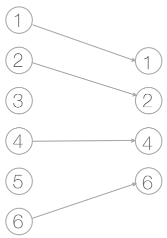
- Certain bits of the input are repeated multiple times in the output
- Example:





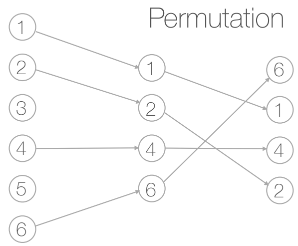
## Choice (Contraction)

- Certain input bits do not appear int the output (they are ignored)
- Example:



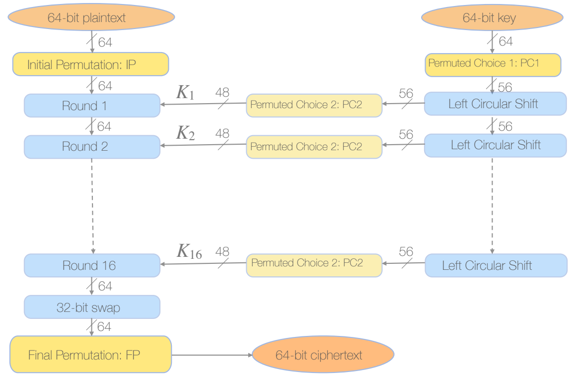


## Permuted Choice




Choice (contraction)

## DES Overview






## DES: IP and FP boxes

- IP and FP are inverses

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 58 | 50 | 42 | 34 | 26 | 18 | 10 | 2 |
| 60 | 52 | 44 | 36 | 28 | 20 | 12 | 4 |
| 62 | 54 | 46 | 38 | 30 | 22 | 14 | 6 |
| 64 | 56 | 48 | 40 | 32 | 24 | 16 | 8 |
| 57 | 49 | 41 | 33 | 25 | 17 | 9 | 1 |
| 59 | 51 | 43 | 35 | 27 | 19 | 11 | 3 |
| 61 | 53 | 45 | 37 | 29 | 21 | 13 | 5 |
| 63 | 55 | 47 | 39 | 31 | 23 | 15 | 7 |

IP

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 40 | 8 | 48 | 16 | 56 | 24 | 64 | 32 |
| 39 | 7 | 47 | 15 | 55 | 23 | 63 | 31 |
| 38 | 6 | 46 | 14 | 54 | 22 | 62 | 30 |
| 37 | 5 | 45 | 13 | 53 | 21 | 61 | 29 |
| 36 | 4 | 44 | 12 | 52 | 20 | 60 | 28 |
| 35 | 3 | 43 | 11 | 51 | 19 | 59 | 27 |
| 34 | 2 | 42 | 10 | 50 | 18 | 58 | 26 |
| 33 | 1 | 41 | 9 | 49 | 17 | 57 | 25 |

FP



## DES: PC1 and PC2 boxes

| | | | | | | |
|---|---|---|---|---|---|---|
| 57 | 49 | 41 | 33 | 25 | 17 | 9 |
| 1 | 58 | 50 | 42 | 34 | 26 | 18 |
| 10 | 2 | 59 | 51 | 43 | 35 | 27 |
| 19 | 11 | 3 | 60 | 52 | 44 | 36 |
| 63 | 55 | 47 | 39 | 31 | 23 | 15 |
| 7 | 62 | 54 | 46 | 38 | 30 | 22 |
| 14 | 6 | 61 | 53 | 45 | 37 | 29 |
| 21 | 13 | 5 | 28 | 20 | 12 | 4 |

PC1 (64 bits in, 56 bits out)

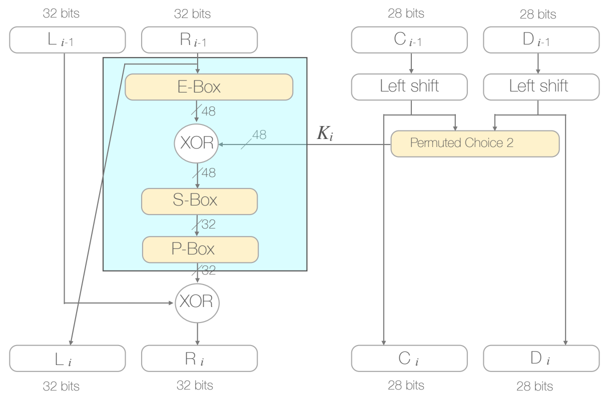
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 14 | 17 | 11 | 24 | 1 | 5 | 3 | 28 |
| 15 | 6 | 21 | 10 | 23 | 19 | 12 | 4 |
| 26 | 8 | 16 | 7 | 27 | 20 | 13 | 2 |
| 41 | 52 | 31 | 37 | 47 | 55 | 30 | 40 |
| 51 | 45 | 33 | 48 | 44 | 49 | 39 | 56 |
| 34 | 53 | 46 | 42 | 50 | 36 | 29 | 32 |

PC2 (56 bits in, 48 bits out)

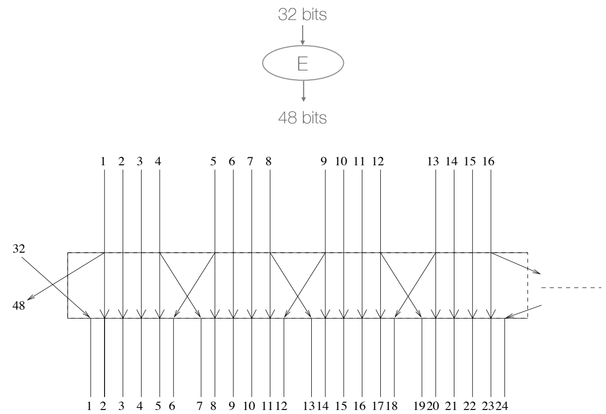
- Bits 8,16, 24, 32, 40, 48, 56, 64 missing in the PC1 box
- Bits 9,18, 25, 35, 38, 43, 45, 54 missing in the PC2 box



## DES: Details of a Round

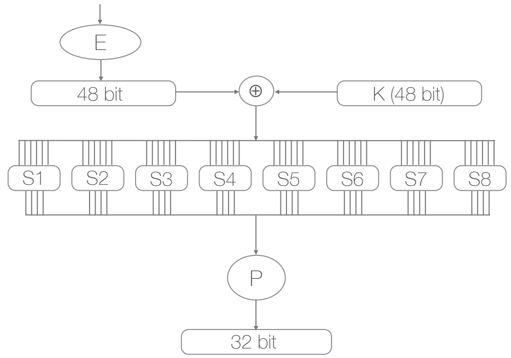


# DES: E-Box





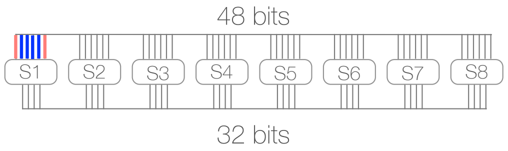

# DES: S-Box






# DES: S-Box

- Bits 1 and 6 select a row, bits 2-5 select a column to read a 4-bit value from one of eight possible maps




S1

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 14 | 04 | 13 | 01 | 02 | 15 | 11 | 08 | 03 | 10 | 06 | 12 | 05 | 09 | 00 | 07 |
| 1 | 00 | 15 | 07 | 04 | 14 | 02 | 13 | 01 | 10 | 06 | 12 | 11 | 09 | 05 | 03 | 08 |
| 2 | 04 | 01 | 14 | 08 | 13 | 06 | 02 | 11 | 15 | 12 | 09 | 07 | 03 | 10 | 05 | 00 |
| 3 | 15 | 12 | 08 | 02 | 04 | 09 | 01 | 07 | 05 | 11 | 03 | 14 | 10 | 00 | 06 | 13 |



# DES: P-Box

- Straight permutation of 32 bits

```
16 07 20 21 29 12 28 17
01 15 23 26 05 18 31 10
02 08 24 14 32 27 03 09
19 13 30 06 22 11 04 25
```

## DES Replacements

- As of 1999, DES is considered *insecure* due to its short key
- More-recent symmetric ciphers that have replaced DES:
  - *Triple-DES* — effectively triples the DES key size
  - *Blowfish* — variable key sizes from 32 bits up to 448 bits
  - *International Data Encryption Algorithm* (IDEA) —128-bit keys
  - *Advanced Encryption Standard* (AES) — key sizes of 128, 192 or 256 bits



## Brute-Force Attacks on Symmetric Ciphers

- Average time required for exhaustive key search as a function of key size

| Key Size (bits) | Number of Alternative Keys | Time Required at 1 Decryption/$\mu$s | Time Required at $10^6$ Decryptions/$\mu$s |
|---|---|---|---|
| 32 | $2^{32} = 4.3 \times 10^9$ | $2^{31}\mu s$ = 35.8 minutes | 2.15 milliseconds |
| 56 | $2^{56} = 7.2 \times 10^{16}$ | $2^{55}\mu s$ = 1142 years | 10.01 hours |
| 128 | $2^{128} = 3.4 \times 10^{38}$ | $2^{127}\mu s = 5.4 \times 10^{24}$ years | $5.4 \times 10^{18}$ years |
| 168 | $2^{168} = 3.7 \times 10^{50}$ | $2^{167}\mu s = 5.9 \times 10^{36}$ years | $5.9 \times 10^{30}$ years |
| 26 characters (permutation) | $26! = 4 \times 10^{26}$ | $2 \times 10^{26}\mu s = 6.4 \times 10^{12}$ years | $6.4 \times 10^6$ years |



## Brute-Force Attacks on Symmetric Ciphers

- A password-cracking expert has unveiled a computer cluster that can cycle through as many as 350 billion guesses per second

Welcome to Radeon City, population: 8. It's one of five servers that make up a high-performance password-cracking cluster.