

Brute force

KOMS119602 - Design and Analysis of Algorithm
(2021/2022)

03 - Brute Force Algorithm

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Part 1: Brute force algorithm

Definition (Brute Force algorithm or Exhaustive Search)

It is a typical problem-solving technique that uses straightforward approach.

The solution is uncovered by **checking every possible answer one by one**, by determining whether the result satisfies the statement of a problem or not.

The algorithm is usually based on:

- problem statement;
- definitions/concepts that are involved in the problem

Characteristics: simple, direct approach, obvious way

Part 1: Brute force algorithm

Example.

- Given an integer n , to find all divisors of n , one could check whether each integer $i \in [1, n]$ can divide n .
- Given a lock of 4-digit PIN, where the digits to be chosen from 0-9. The brute force will be trying all possible combinations one by one like 0001, 0002, 0003, 0004, and so on until we get the right PIN (there are at most 10000 trials).

1. Searching the max/min element of an array

Problem. Given an array of n integers (a_1, a_2, \dots, a_n) . We want to find the maximum of the array.

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Brute-force approach: to find the max, compare each element from a_1 to a_n .

Algorithm 2 Finding maximum of an array of integers

```
1: procedure MAX( $A[1..n]$ )
2:    $\text{max} \leftarrow a_1$ 
3:   for  $i = 2$  to  $n$  do
4:     if  $a_i > \text{max}$  then
5:        $\text{max} \leftarrow a_i$ 
6:     end if
7:   end for
8: end procedure
```

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Algorithm 3 Finding maximum of an array of integers

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6:     end if
7:   end for
8: end procedure
```

Complexity? $\mathcal{O}(n)$

2. Sequential search

Problem. Given an array of integers (a_1, a_2, \dots, a_n) . We want to find an element x in the array. If x is found, the algorithm outputs the index of the element in the array. Otherwise, it outputs -1 .

Brute-force approach: compare each element in the array with x . We are done if x is found or all elements are checked.

2. Sequential search

Algorithm 4 Finding an element in an array of integers

```
1: procedure SEQSEARCH( $A[1..n], x$ )
2:    $i \leftarrow 1$ 
3:   while  $i < n$  and  $a_i \neq x$  do
4:      $i \leftarrow i + 1$ 
5:   end while
6:   if  $a_i = x$  then
7:      $\text{idx} \leftarrow i$ 
8:   else
9:      $\text{idx} \leftarrow -1$ 
10:  end if
11:  return  $\text{idx}$ 
12: end procedure
```

Complexity? in the assignment!

3. Powering

Problem. Compute a^n ($a > 0$, n is a non-negative numbers).

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Brute-force approach:

$$a^n = a \times a \times \cdots \times a \quad n \text{ times}$$

We multiply 1 with a n times.

Algorithm 6 Computing a^n

```
1: procedure POWER( $a, n$ )
2:   result  $\leftarrow$  1
3:   for  $i = 1$  to  $n$  do
4:     result  $\leftarrow$  result *  $a$ 
5:   end for
6:   return result
7: end procedure
```

3. Powering

Algorithm 5 Computing a^n

```
1: procedure POWER( $a, n$ )  
2:   result  $\leftarrow$  1  
3:   for  $i = 1$  to  $n$  do  
4:     result  $\leftarrow$  result *  $a$   
5:   end for  
6:   return result  
7: end procedure
```

Time complexity: $\mathcal{O}(n)$.

Can you explain why?

Is there a better algorithm for "power"?

4. Computing factorial

Problem. Compute $n!$ ($n > 0$, n is a non-negative integers).

Brute-force approach:

$$n! = 1 \times 2 \times \cdots \times n \text{ and } 0! = 1$$

We multiply the integers 1, 2, until n

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We multiply the integers 1, 2, until n

Algorithm 8 Computing $n!$

```
1: procedure FACTORIAL( $n$ )
2:   result  $\leftarrow$  1
3:   if  $n \leq 1$  then return result
4:   else
5:     for  $i = 2$  to  $n$  do
6:       result  $\leftarrow$  result *  $i$ 
7:     end for
8:   end if
9:   return result
10: end procedure
```

4. Computing factorial

Algorithm 5 Computing $n!$

```
1: procedure FACTORIAL( $n$ )
2:   result  $\leftarrow$  1
3:   if  $n \leq 1$  then return result
4:   else
5:     for  $i = 2$  to  $n$  do
6:       result  $\leftarrow$  result *  $i$ 
7:     end for
8:   end if
9:   return result
10: end procedure
```



Time complexity: $\mathcal{O}(n)$ (multiplying n numbers)

5. Square matrix multiplication

Problem. Given two square matrices, of size $n \times n$.
Find a way to multiply the two matrices!

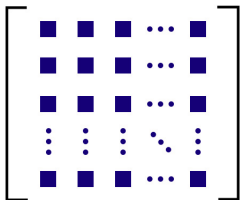
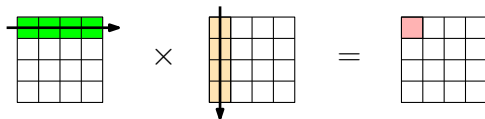


Figure: A square matrix

5. Square matrix multiplication

Let $A = [a_{ij}]$, $B = [b_{ij}]$ be $n \times n$ matrices, and $C = A \times B$.

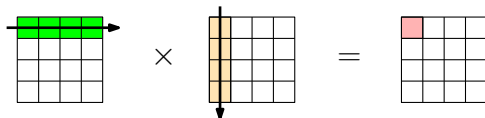
$$c_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \cdots + a_{in}b_{nj} = \sum_{k=1}^n a_{ik}b_{kj}$$



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Let $A = [a_{ij}]$, $B = [b_{ij}]$ be $n \times n$ matrices, and $C = A \times B$.

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Brute-force approach: compute each element of C one-by-one by multiplying the corresponding row of A and column of B .

5. Square matrix multiplication

Algorithm 9 Square matrix multiplication

```
1: procedure MATRIXMULT( $A, B$ )
2:   for  $i \leftarrow 1$  to  $n$  do
3:     for  $j \leftarrow 1$  to  $n$  do
4:        $C[i, j] \leftarrow 0$ 
5:       for  $k \leftarrow 1$  to  $n$  do
6:          $C[i, j] \leftarrow C[i, j] + A[i, k] * B[k, j]$ 
7:       end for
8:     end for
9:   end for
10:  return  $C$ 
11: end procedure
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7:       end for
8:     end for
9:   end for
10:  return  $C$ 
11: end procedure
```

Time complexity: $\mathcal{O}(n^3)$.

We look at the "dominant operations" as follows:

- Inside the inner-most loop: n^3 multiplications, n^3 additions, and n^3 assignments
- Inside the second loop: n^2 assignments

6. Prime number test

Problem. Given a positive integer n . Check if n is prime.

Remark. A number n is *prime* iff the only divisors of n are 1 and n .

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1. Brute-force approach: divide n by $2, 3, \dots, n - 1$. If none of them divides n , then n is a prime number.

6. Prime number test

Algorithm 10 Prime number test

```
1: procedure ISPRIME( $n$ )
2:   if  $n < 2$  then
3:     return False
4:   else
5:     isprime  $\leftarrow$  True;  $k \leftarrow 2$ 
6:     while isprime & ( $k \leq n - 1$ ) do
7:       if  $n \bmod k == 0$  then
8:         isprime  $\leftarrow$  False
9:       else
10:         $k \leftarrow k + 1$ 
11:      end if
12:    end while
13:    return isprime
14:  end if
15: end procedure
```

6. Prime number test

Problem. Given a positive integer n . Check if n is prime.

Remark. A number n is prime iff the only divisors of n are 1 and n .

1. Brute-force approach: divide n by $2, 3, \dots, n - 1$. If none of them divides n , then n is a prime number.

2. Sieve of Eratosthenes: for a given upper limit n , iteratively mark the multiples of primes as *composite* (i.e. not prime), starting from 2. Once all multiples of 2 have been marked composite, the multiples of next prime, i.e. 3 are marked composite. This process continues until $p \leq \sqrt{n}$, where p is a prime number.

By this technique, to check that n is prime, we only need to **check if there is any prime number $\leq \sqrt{n}$ that divides n .**

6. Prime number test

Algorithm 11 Prime number test (*sieve of Eratosthenes*)

```
1: procedure ISPRIME2( $n$ )
2:   if  $n < 2$  then
3:     return False
4:   else
5:     isprime  $\leftarrow$  True;  $k \leftarrow 2$ 
6:     while isprime & ( $k \leq \sqrt{n}$ ) do
7:       if  $n \bmod k == 0$  then
8:         isprime  $\leftarrow$  False
9:       else
10:         $k \leftarrow k + 1$ 
11:      end if
12:    end while
13:    return isprime
14:  end if
15: end procedure
```

6. Prime number test

Time complexity:

Algorithm 8 Prime number test

```
1: procedure ISPRIME( $n$ )
2:   if  $n < 2$  then
3:     return False
4:   else
5:     isprime  $\leftarrow$  True;  $k \leftarrow 2$ 
6:     while test & ( $k \leq n - 1$ ) do
7:       if  $n \bmod k == 0$  then
8:         isprime  $\leftarrow$  False
9:       else
10:         $k \leftarrow k + 1$ 
11:      end if
12:    end while
13:    return test
14:  end if
15: end procedure
```

Algorithm 9 Prime number test (sieve of Eratosthenes)

```
1: procedure ISPRIME2( $n$ )
2:   if  $n < 2$  then
3:     return False
4:   else
5:     isprime  $\leftarrow$  True;  $k \leftarrow 2$ 
6:     while test & ( $k \leq \sqrt{n}$ ) do
7:       if  $n \bmod k == 0$  then
8:         isprime  $\leftarrow$  False
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```

- Brute-force: $\mathcal{O}(n)$
- Sieve-Erathosthenes brute-force: $\mathcal{O}(\sqrt{n})$

7. Polynomial interpolation

Problem. Evaluate the following polynomial at $x = t$:

$$p(x) = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_1 x + a_0$$

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$$p(x) = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_1 x + a_0$$

Brute-force approach: each of x^k is computed as in the "powering algorithm"; then multiply x^k with a_k , and take the sum with the other terms.

7. Polynomial interpolation

Algorithm 12 Polynomial interpolation

```
1: procedure POLYNOM( $n, A[0..n], t$ )
2:    $p \leftarrow 0$ 
3:   for  $i \leftarrow n$  downto 0 do
4:     power  $\leftarrow 1$ 
5:     for  $j \leftarrow 1$  to  $i$  do
6:       power  $\leftarrow$  power  $\ast t$ 
7:     end for
8:      $p \leftarrow p + a[i] \ast$  power
9:   end for
10:  return  $p$ 
11: end procedure
```

7. Polynomial interpolation

Algorithm 13 Polynomial interpolation

```
1: procedure POLYNOM( $n, A[0..n], t$ )
2:    $p \leftarrow 0$ 
3:   for  $i \leftarrow n$  downto 0 do
4:     power  $\leftarrow 1$ 
5:     for  $j \leftarrow 1$  to  $i$  do
6:       power  $\leftarrow$  power *  $t$ 
7:     end for
8:      $p \leftarrow p + a[i] * \text{power}$ 
9:   end for
10:  return  $p$ 
11: end procedure
```

There are $\mathcal{O}(\frac{n(n-1)}{2}) + \mathcal{O}(n + 1)$ operations.

Time complexity: $\mathcal{O}(n^2)$.

8. Closest pair problem

Problem. Given n points in the 2 dimensional Euclidean space (i.e. Cartesian coordinate system). Find two points with the shortest distance.

The distance between two points $p_1(x_1, y_1)$ and $p_2 = (x_2, y_2)$ is given by:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

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$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

Brute-force approach:

- 1 Compute the distance between every pair of points
- 2 Take the pair with the minimum distance

8. Closest pair problem

Algorithm 14 Finding the closest points

```
1: procedure CLOSESTPOINTS( $p_1, p_2, \dots, p_n$ )
2:    $d_{\min} \leftarrow 999999$ 
3:   for  $i \leftarrow 1$  to  $n - 1$  do
4:     for  $j \leftarrow i + 1$  to  $n$  do
5:        $d \leftarrow \sqrt{(p_i.x - p_j.x)^2 + (p_i.y - p_j.y)^2}$ 
6:       if  $d < d_{\min}$  then
7:          $d_{\min} \leftarrow d$ 
8:          $A \leftarrow p_i$ 
9:          $B \leftarrow p_j$ 
10:      end if
11:    end for
12:  end for
13:  return  $A$  and  $B$ 
14: end procedure
```

8. Closest pair problem

Algorithm 13 Finding the closest points

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1: procedure CLOSESTPOINTS( $p_1, p_2, \dots, p_n$ )
2:    $dmin \leftarrow 999999$ 
3:   for  $i \leftarrow 1$  to  $n - 1$  do
4:     for  $j \leftarrow i + 1$  to  $n$  do
5:        $d \leftarrow \sqrt{(p_i.x - p_j.x)^2 + (p_i.y - p_j.y)^2}$ 
6:       if  $d < dmin$  then
7:          $dmin \leftarrow d$ 
8:          $A \leftarrow p_i$ 
9:          $B \leftarrow p_j$ 
10:      end if
11:    end for
12:  end for
13:  return  $A$  and  $B$ 
14: end procedure
```

Time complexity: $\mathcal{O}(n^2)$

9. Pattern matching

Problem. Given a *string of length n* and a *pattern of length m* with $m < n$. Find the location of the first character of the pattern in the string that matches with the pattern.

Example.

- **String:** NOBODY NOTICED HIM
- **Pattern:** NOT

9. Pattern matching

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Example.

- **String:** NOBODY NOTICED HIM
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Brute-force approach:

- ① Start with the first character of the string.
- ② Start from the first character of the pattern, check if the pattern matches with some substring:
 - all characters match
 - there is a character that doesn't match
- ③ If the pattern doesn't match, we move to the right, and repeat Step 2.

9. Pattern matching

Example 1.

N O B O D Y _ N O T I C E D _ H I M
N O N T O T T T T T T T T
N O N T O N O N O N O N O T

Example 2.

- 10010101001011110101010001
- 001011

10010101**001011**110101010001 (Try it!)

9. Pattern matching

```
1: procedure PATTERNMATCHING( $P, T$ )
2:    $i \leftarrow 0$ ; found  $\leftarrow$  False
3:   while ( $i \leq n - m$ ) & (not found) do
4:      $j \leftarrow 1$ 
5:     while ( $j \leq m$ ) and  $P_j = T_{i+j}$  do
6:        $j \leftarrow j + 1$ 
7:     end while
8:     if  $j = m$  then found  $\leftarrow$  True
9:     else  $i \leftarrow i + 1$ 
10:    end if
11:  end while
12:  if found then return  $i + 1$ 
13:  else return  $-1$ 
14:  end if
15: end procedure
```

9. Pattern matching

Time complexity

① Worst case

- In each matching trial, we match all characters of the pattern with the character in the corresponding character of the string $\rightarrow m$ steps
- This is done for all possible positions in the string $\rightarrow n - m + 1$ possibilities
- The number of steps: $m(n - m + 1) \in \mathcal{O}(nm)$

② Best case

- This happens when the pattern is found in the first m positions of the string
- In this case, we check all characters of the pattern
- Complexity: $\mathcal{O}(m)$

Strength of brute-force:

- This is not a powerful algorithm, but almost all problems can be solved using brute force algorithm.
- Simple and easy to understand
- Can be applied for many problems: searching, sorting, string matching, matrix multiplication, etc.
- It produces standard algorithms for computational tasks such as multiplication/addition of n numbers, finding max/min in an array.

Drawbacks of brute-force:

- The algorithm is **not "smart"**, because it needs many computation and takes long time to proceed. For many real-world problems, the number of natural candidates is prohibitively large.
- Brute force algorithm is **suitable for small instance**, because it is simple and can be easily implemented.

Remark. This algorithm is often called as *naive algorithm*, and is used to compare with the other powerful algorithm.

Part 2: Exhaustive search

Exhaustive search is simply a brute-force approach to *combinatorial problems* (permutation, combination, subsets, etc.).

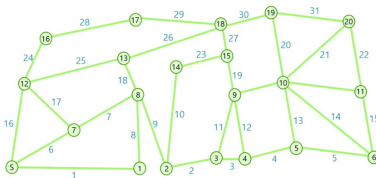
Remark. Example of combinatorial problems are the Traveling Salesman Problem, Knapsack problem, etc.; and non-combinatorial problems are Powering problem, Square Matrix Multiplication, etc.

Remark. In many references, exhaustive search is considered same as brute force.

Read the book of Anany Levitin, look at Section 3.4 (page 143)!

1. Traveling Salesman Problem (page 142)

Problem. Given n cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?



Remark. We may always assume that the given input graph is a **complete graph** (i.e. every pair of vertices is joined by an edge). If as in the figure above the graph is not complete (for example, there is no edge between vertex 1 and 7, then we may assume that the edge $(1,7)$ exists, but its weight is ∞).

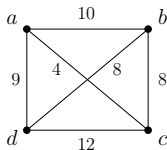
1. Traveling Salesman Problem (page 142)

Hamiltonian cycle is a cycle that visits each vertex of the graph exactly once. The TSP problem is equivalent to *finding the Hamiltonian cycle of the minimum weight*.

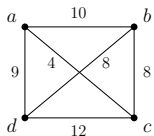
Exhaustive search algorithm for TSP

- 1 Enumerate all Hamiltonian cycles of an n -vertex complete graph.
- 2 Evaluate the weight of every Hamiltonian cycle that is found in step 1.
- 3 Choose the Hamiltonian cycle with the minimum weight.

Exercise. Apply the algorithm above to the following graph!

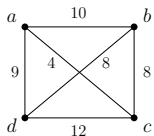


1. Traveling Salesman Problem (page 142)



No.	Traveling route	Weight
1.	$a \rightarrow b \rightarrow c \rightarrow d \rightarrow a$	$10 + 8 + 12 + 9 = 39$
2.	$a \rightarrow b \rightarrow d \rightarrow c \rightarrow a$	$10 + 8 + 12 + 4 = 34$
3.	$a \rightarrow c \rightarrow b \rightarrow d \rightarrow a$	$4 + 8 + 8 + 9 = 29$
4.	$a \rightarrow c \rightarrow d \rightarrow b \rightarrow a$	$4 + 12 + 8 + 10 = 34$
5.	$a \rightarrow d \rightarrow b \rightarrow c \rightarrow a$	$9 + 8 + 8 + 4 = 29$
6.	$a \rightarrow d \rightarrow c \rightarrow b \rightarrow a$	$9 + 12 + 8 + 10 = 39$

1. Traveling Salesman Problem (page 142)



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5.	$a \rightarrow d \rightarrow b \rightarrow c \rightarrow a$	$9 + 8 + 8 + 4 = 29$
6.	$a \rightarrow d \rightarrow c \rightarrow b \rightarrow a$	$9 + 12 + 8 + 10 = 39$

The shortest route is given by:

- $a \rightarrow c \rightarrow b \rightarrow d \rightarrow a$, of weight 29
- $a \rightarrow d \rightarrow b \rightarrow c \rightarrow a$, of weight 29

1. Traveling Salesman Problem (page 142)

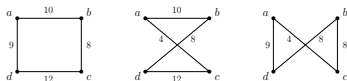
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- 1 Enumerate all Hamiltonian cycle of an n -vertex complete graph.
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- 3 Choose the Hamiltonian cycle with the minimum weight.

Discuss how to compute the complexity?

Time complexity of exhaustive search of TSP

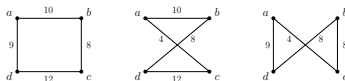
- Up to shifting, the number of different Hamiltonian cycles on n vertices is: $\frac{(n-1)!}{2}$ (use the "cyclic permutation formula" (https://www.wikiwand.com/en/Cyclic_permutation), and note that the solution set can be grouped into pairs where one is the reflection of the other).



- So, to solve TSP with exhaustive search, then we have to enumerate $\frac{(n-1)!}{2}$ Hamiltonian cycles, compute their weights, and choose the cycle that has the minimum weight.
- To compute the weight of a cycle, we need $\mathcal{O}(n)$ -time.
- Hence, the complexity is: $\frac{(n-1)!}{2} \cdot \mathcal{O}(n) \in \mathcal{O}(n \cdot n!)$ (not powerful).

Time complexity of exhaustive search of TSP

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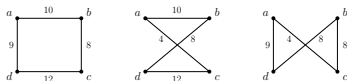


- So, to solve TSP with exhaustive search, then we have to enumerate $\frac{(n-1)!}{2}$ Hamiltonian cycles, compute their weights, and choose the cycle that has the minimum weight.
- To compute the weight of a cycle, we need $\mathcal{O}(n)$ -time.
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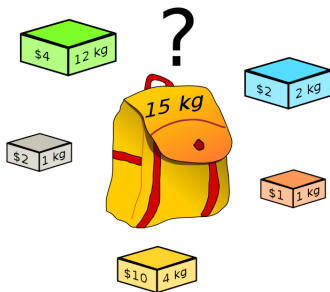


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 $\approx 1,541,911,905,814$ years

2. The 1/0 knapsack problem (page 143)

Given n items and a knapsack of capacity K . Every object i has weight w_i and profit p_i . Determine the way to select the objects to the knapsack so that the profit is maximum. The total weight of the objects can not exceed the knapsack's capacity.



Remark. 1/0 knapsack means that an object can be included to the knapsack (1) or not included (0).

2. The 1/0 knapsack problem (page 143)

Write the solution as $X = \{x_1, x_2, \dots, x_n\}$ where:

- $x_i = 1$, if the i^{th} object is selected
- $x_i = 0$ otherwise

The mathematical formulation of the 1/0 knapsack problem:

Definition (math formulation of 1/0 knapsack)

$$\text{Maximize } F = \sum_{i=1}^n p_i x_i$$

$$\text{subject to } \sum_{i=1}^n w_i x_i \leq K$$

$$\text{and } x_i = 0 \text{ or } x_i = 1, \text{ for } i = 1, 2, \dots, n$$

- **Maximize F** : the optimization function
- **subject to ...** : the constraints (i.e. limitation)

2. The 1/0 knapsack problem (page 143)

Exhaustive search for 1/0 knapsack problem:

- 1 Enumerate all subsets of a set on n elements
- 2 Evaluate the profit of every subset instep 1
- 3 Choose the subset that gives the maximum profit but whose weight does not exceed the knapsack's capacity

2. The 1/0 knapsack problem (page 143)

Given four objects and a knapsack of capacity $K = 16$. The property of each object is summarized in the following table:

Object	Weight	Profit
1	2	20
2	5	30
3	10	50
4	5	10

2. The 1/0 knapsack problem (page 143)

Subset	Weight	Profit
$\{\}$	0	0
$\{1\}$	2	20
$\{2\}$	5	30
$\{3\}$	10	50
$\{4\}$	5	10
$\{1, 2\}$	7	50
$\{1, 3\}$	12	70
$\{1, 4\}$	7	30

Subset	Weight	Profit
$\{2, 3\}$	15	80
$\{2, 4\}$	10	40
$\{3, 4\}$	15	60
$\{1, 2, 3\}$	17	not feasible
$\{1, 2, 4\}$	12	60
$\{1, 3, 4\}$	17	not feasible
$\{2, 3, 4\}$	20	not feasible
$\{1, 2, 3, 4\}$	22	not feasible

The **optimal solution** is given by the subset $\{2, 3\}$ with profit is 80. So the solution of the problem is given by $X = \{0, 1, 1, 0\}$ (the objects 1 and 4 are not taken, and objects 2 and 3 are taken).

Remark. A solution candidate is "not feasible", because the total weight exceeds the knapsack capacity.

2. The 1/0 knapsack problem (page 143)

Time complexity:

- The number of subsets of a set of n elements is: 2^n .
- Time to compute the total weight of a subset is: $\mathcal{O}(n)$.
- So, the complexity of exhaustive search for 1/0 knapsack problem is: $\mathcal{O}(n \cdot 2^n)$ (exponential complexity).

Exhaustive search in cryptography

Exhaustive search is used in cryptography as a technique that is used by an attacker to find a decryption key by trying all possible keys, known as **exhaustive key search attack** or **brute force attack**.

Example

The length of encryption key in DES (Data Encryption Standard) algorithm is 64 bits.

- From that 64 bits, only 56 bits are used, while the other 8 bits are used as parity checking.
- The number of combination for the key is $2^{56} = 72,057,594,037,927,936$
- This means that if the time needed to try one combination is 1 second, then to try all combinations, it would take 2,284,931,317 years.

Exercises: 1. Assignment problem (page 145)

Given n staffs and n tasks. Everyone is assigned to a task. The staff(s_i) is assigned to the task(t_j) with cost $c(i, j)$. Design a brute force algorithm to assign the tasks such that the total cost $\sum c(i, j)$ is minimized. The instance of the problem is represented in the following matrix.

Example.

Cost matrix:

$$C = \begin{bmatrix} \text{task 1} & \text{task 2} & \text{task 3} & \text{task 4} \\ 9 & 2 & 7 & 8 \\ 6 & 4 & 3 & 7 \\ 5 & 8 & 1 & 8 \\ 7 & 6 & 9 & 4 \end{bmatrix} \begin{matrix} \text{staff a} \\ \text{staff b} \\ \text{staff c} \\ \text{staff d} \end{matrix}$$

Exercises: 1. Assignment problem (page 145)

Remark. An instance of the assignment problem is completely specified by its cost matrix.

Question. How do you view a solution in terms of this matrix?

Exercises: 1. Assignment problem (page 145)

Remark. An instance of the assignment problem is completely specified by its cost matrix.

Question. How do you view a solution in terms of this matrix?

The first few iterations of solving a small instance of the assignment problem by exhaustive search.

$$C = \begin{bmatrix} 9 & 2 & 7 & 8 \\ 6 & 4 & 3 & 7 \\ 5 & 8 & 1 & 8 \\ 7 & 6 & 9 & 4 \end{bmatrix}$$

$\langle 1, 2, 3, 4 \rangle$	cost = $9 + 4 + 1 + 4 = 18$
$\langle 1, 2, 4, 3 \rangle$	cost = $9 + 4 + 8 + 9 = 30$
$\langle 1, 3, 2, 4 \rangle$	cost = $9 + 3 + 8 + 4 = 24$
$\langle 1, 3, 4, 2 \rangle$	cost = $9 + 3 + 8 + 6 = 26$
$\langle 1, 4, 2, 3 \rangle$	cost = $9 + 7 + 8 + 9 = 33$
$\langle 1, 4, 3, 2 \rangle$	cost = $9 + 7 + 1 + 6 = 23$
\vdots	\vdots

Remark. $\langle k, l, m, n \rangle$ means the entries $c_{1,k}, c_{2,l}, c_{3,m}, c_{4,n}$.

Complexity

- The number of choices: $n \cdot (n - 1) \cdot (n - 2) \cdot \dots \cdot 1$
- Complexity: $\mathcal{O}(n^2)$

Exercises: 2. Partition problem

Given n positive integers. Divide them into two disjoint sets such that the sum of the two subsets are equal. Design an exhaustive search algorithm for this problem.

Example. $n = 6$, and the integers are 3, 8, 4, 6, 1, 2. It can be divided into $\{3, 8, 1\}$ and $\{4, 6, 2\}$, where the sum of each of them is 12.

Question. How do we obtain this solution?

Exercises: 2. Partition problem

Algorithm

Input: set S

Output: a subset $A \subseteq S$ satisfying $\text{sum}(A) = \frac{\text{sum}(S)}{2}$

- 1 Enumerate all possible subsets of S ;
- 2 For every subset $A \subseteq S$, check whether $\text{sum}(A) = \frac{\text{sum}(S)}{2}$;

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- 2 For every subset $A \subseteq S$, check whether $\text{sum}(A) = \frac{\text{sum}(S)}{2}$;

Time complexity: $\mathcal{O}(2^n)$

(because a set of n elements has 2^n subsets).

Exercises: 3. Magic square

A **magic square** is an arrangement of n numbers from 1 to n^2 in a square of size $n \times n$ such that the sum of every column, row, and diagonal are equal. Design an exhaustive search algorithm to build a magic square of order n .

4	9	2
3	5	7
8	1	6

Exercises: 3. Magic square

Algorithm

Input: $(1, 2, 3, \dots, n^2)$

Output: a magic square of size $n \times n$

- 1 Enumerate all possible square;
- 2 For each of them, check if it is a magic square (by checking whether the sum of every row, column, and diagonal is equal).

Exercises: 3. Magic square

Algorithm

Input: $(1, 2, 3, \dots, n^2)$

Output: a magic square of size $n \times n$

- 1 Enumerate all possible square;
- 2 For each of them, check if it is a magic square (by checking whether the sum of every row, column, and diagonal is equal).

Complexity: $\mathcal{O}(n!)$ because there are $n!$ possible square

Task: Write the pseudocode for those three exercises!

Part 3: Heuristic technique

To read:

[https://www.wikiwand.com/en/Heuristic_\(computer_science\)](https://www.wikiwand.com/en/Heuristic_(computer_science))

Heuristic is a technique designed for solving a problem more quickly when classic methods are too slow or for finding an approximate solution when classic methods fail to find any exact solution.

- The objective of a heuristic is to produce a solution in a reasonable time frame that is good enough for solving the problem.
- Heuristic uses *guessing*, *intuition*, and *common sense* which cannot be proved mathematically.
- It doesn't always give an optimal solution.
- A good heuristic can extremely reduce the time to solve a problem by eliminating unnecessary solution candidates.
- No guarantee that heuristic can solve a problem, but it works many times and often faster than exhaustive search.

Part 3: Heuristic technique

Heuristic technique can be used to **reduce the number of possible candidates of the problem's solution.**

Example

In **anagram** problem, for English we can use the rule that the letters "c" and "h" often appear consecutively in English words. So we can consider only the permutation of letters where "ch" appear together.

Example.

- march → charm
- chapter → patcher, repatch

Example

To solve the magic square problem with exhaustive search, we have to check $9! = 362,880$ possible solution, then check whether for each of them, the sum of every column, row, and diagonal are equal.

With the heuristic technique, for each of the solution, we can check whether the first column has $sum = 15$. If yes, we check the next column/row. Otherwise, we stop, and check the other permutation.

Trade-off: When to choose heuristic technique?

- **Optimality:** When several solutions exist for a given problem, does the heuristic guarantee that the best solution will be found? Is it actually necessary to find the best solution?
- **Completeness:** When several solutions exist for a given problem, can the heuristic find them all? Do we actually need all solutions? Many heuristics are only meant to find one solution.
- **Accuracy and precision:** Can the heuristic provide a confidence interval for the purported solution? Is the error bar on the solution unreasonably large?
- **Execution time:** Is this the best known heuristic for solving this type of problem?