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CSC 401 - Advanced Topics in Algorithms

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# 1 Question 1

**a**  $A(n) = 3A(n/4) + n^{(3/4)}$

$$A(n) = \Theta(n^{\log_3 4})$$

*Proof.* Inspection using Iteration method

$$\begin{aligned} A(n) &= 3A\left(\frac{n}{4}\right) + n^{(3/4)} \\ &= 9A\left(\frac{n}{16}\right) + 3\left(\frac{n}{4}\right)^{3/4} + n^{3/4} \\ &\vdots \\ &= 3^k A\left(\frac{n}{4^k}\right) + 3^{k-1}\left(\frac{n}{4^{k-1}}\right)^{3/4} + \dots + 3\left(\frac{n}{4}\right)^{3/4} + n^{3/4} \\ &= 3^k A(1) + \sum_{i=0}^{k-1} 3^{k-1}\left(\frac{n}{4^{k-1}}\right)^{3/4} \end{aligned}$$

Given that  $A(1)$  is a constant (say  $C_1$ )

$$= 3^k C_1 + n^{3/4} \sum_{i=0}^{k-1} \frac{3^i}{4^{3i/4}}$$

$\sum_{i=0}^{k-1} 3^i / (4^{3i/4})$  is a numerical constant, taking it as  $C_2$

$$\begin{aligned} &= (4^k)^{\log_3 4} C_1 + n^{3/4} C_2 \\ &= n^{\log_3 4} C_1 + n^{3/4} C_2 \end{aligned}$$

$$n^{\log_3 4} = n^{0.79}, n^{3/4} = n^{0.75}$$

Therefore  $n^{\log_3 4}$  is the dominating term and,

$$A(n) = \Theta(n^{\log_3 4})$$

Verification using Master Theorem,

$$\begin{aligned} A(n) &= 3A\left(\frac{n}{4}\right) + n^{(3/4)} \\ a &= 3, \\ b &= 4, \text{ and,} \\ f(n) &= n^{3/4} \end{aligned}$$

Is  $f(n) = \mathcal{O}(n^{\log_b a - \epsilon})$ ?

$$\log_b a = \log_3 4 = 0.79$$

Because,  $n^{\log_3 4} = n^{0.79}$ , therefore,

$$\begin{aligned} f(n) &= n^{3/4} = n^{0.75} \\ &= \mathcal{O}(n^{\log_3 4 - \epsilon}) \end{aligned}$$

where,  $\epsilon = 0.04$

Therefore, by Case 1 of the Master Theorem,

$$A(n) = \Theta(n^{\log_3 4})$$

□

$$\mathbf{b} \quad B(n) = B(n-2) + n \lg n$$

$$B(n) = \mathcal{O}(n^2 \lg n)$$

*Proof.*

$$\begin{aligned} B(n) &= B(n-2) + n \lg n \\ &= B(n-4) + (n-2) \lg(n-2) + n \lg n \\ &\vdots \\ &= B(n-2k) + (n-2k+2) \lg(n-2k+2) + \cdots \\ &\quad + \cdots + (n-2) \lg(n-2) + n \lg n \end{aligned}$$

Choosing  $k$  such that  $n-2k=1$  or  $n-2k=0$

Therefore  $B(n-2k) = \text{constant}(=c, \text{ say})$

$$B(n) = c + (n-2k+2) \lg(n-2k+2) + \cdots + (n-2) \lg(n-2) + n \lg n$$

$f(n) = n \lg n$ , being the product of two increasing functions,  $f_1(n) = n$  and  $f_2 = \lg n$ , is a strictly increasing function

We can therefore say that

$$\begin{aligned} (n-2) \lg(n-2) &< (n-2) \lg n, \\ (n-4) \lg(n-4) &< (n-4) \lg n, \\ &\vdots \\ (n-2k+2) \lg(n-2k+2) &< (n-2k+2) \lg n \end{aligned}$$

Therefore,

$$\begin{aligned} B(n) &= c + (n-2k+2) \lg(n-2k+2) + \cdots + (n-2) \lg(n-2) + n \lg n \\ &< c + (n-2k+2) \lg n + \cdots + (n-2) \lg n + n \lg n \\ &< c + \lg n((n-2k+2) + \cdots + (n-4) + (n-2) + n) \\ &< c + \lg n\left(\frac{n(n-1)}{4}\right) \\ &< c + \left(\frac{n^2}{4}\right) \lg n - \left(\frac{n}{4}\right) \lg n \end{aligned}$$

Therefore,

$$B(n) = \mathcal{O}(n^2 \lg n)$$

□

$$\mathbf{c} \quad C(n) = C(\lceil n/3 \rceil) + \lceil n/2 \rceil$$

$$C(n) = \Theta(n)$$

*Proof.* Transforming using Akra-Bazzi Theorem,

$$\begin{aligned} C(n) &= C(\lceil n/3 \rceil) + \lceil n/2 \rceil \\ C(n) &= \lceil n/2 \rceil + C(\lceil n/3 \rceil) \\ C(n) &= \lceil n/2 \rceil + C(n/3 + h(n)) \text{ where } h(n) = \lceil n/3 \rceil - n/3 \end{aligned} \quad \dots (1)$$

Since  $0 < \lceil n/3 \rceil - n/3 < 1$

$$h(n) = \mathcal{O}(1)$$

By Akra-Bazzi Theorem, the above at (1) has the same order as,

$$\begin{aligned} C'(n) &= \lceil n/2 \rceil + C'(n/3) \\ &= n/2 + (\lceil n/2 \rceil - n/2) + C'(n/3) \end{aligned}$$

Let's define a function  $f(x) = \lceil x \rceil - x$ ,

$$\begin{aligned} C'(n) &= n/2 + f(n/2) + C'(n/3) \\ &= n/2 + n/6 + f(n/2) + f(n/6) + C'(n/9) \\ &\vdots \\ &= \frac{n}{2} \left( 1 + \frac{1}{3} + \frac{1}{9} + \dots + \frac{1}{3^k} \right) \\ &\quad + f\left(\frac{n}{2}\right) + f\left(\frac{n}{6}\right) + \dots + f\left(\frac{n}{2 \cdot 3^k}\right) \\ &\quad + C'(n/3^k) \dots \text{where } k \text{ is such that } \frac{n}{3^k} \text{ is a small fraction} \end{aligned}$$

Now let,

$$\begin{aligned} a &= 1 + \frac{1}{3} + \frac{1}{9} + \dots + \frac{1}{3^k} \text{ and,} \\ b &= f\left(\frac{n}{2}\right) + f\left(\frac{n}{6}\right) + \dots + f\left(\frac{n}{2 \cdot 3^k}\right) \end{aligned}$$

Also, we know that for small constants,

$C'(n)$  will have constant(say,  $= X_3$ ),  $\mathcal{O}(1)$  values,

Therefore,

$$C'(n) = \frac{n}{2}a + b + X_3$$

Examining the term a,

We know from the theory of geometric progressions that,

$$\sum_{i=0}^n cr^i = \frac{c(1-r^{n+1})}{1-r}$$

$$a = 1 + \frac{1}{3} + \frac{1}{9} + \cdots + \frac{1}{3^k}$$

Therefore, for us,  $c = 1$ ,  $r = \frac{1}{3}$  and  $n = k - 1$

$$a = 1 * \left( \frac{1 - \frac{1}{3}^k}{1 - \frac{1}{3}} \right)$$

$$= \text{a numerical constant } (= X_1, \text{ say})$$

Now, examining the term  $b$ ,

Since  $0 \leq f(x) < 1$  for any  $x$ ,

$$b = f\left(\frac{n}{2}\right) + f\left(\frac{n}{6}\right) + \cdots + f\left(\frac{n}{2 * 3^k}\right)$$

$$\max(b) < 1 + 1 + \cdots + 1$$

$$= \log_3 n$$

$$= \frac{\lg n}{\lg 3} \text{ and,}$$

$$\min(b) = 0 + 0 + \cdots + 0$$

$$= 0$$

Therefore,

$$C'(n) = \frac{n}{2}X_1 + b + X_3$$

$$< \frac{n}{2}X_1 + \frac{\lg n}{\lg 3} + X_3$$

Hence,

$$C'(n) = \mathcal{O}(n) \quad \dots (2)$$

Also,

$$C'(n) = \frac{n}{2}X_1 + b + X_3$$

$$\geq \frac{n}{2}X_1 + 0 + X_3$$

Hence,

$$C'(n) = \Omega(n) \quad \dots (3)$$

Thus, from (2) and (3) we can conclude,

$$C'(n) = \Theta(n)$$

□

## 2 Question 2

### a Farthermost pair of vertices of a convex polygon

We shall use a slight modification of the rotating-callipers algorithm to find our answer. We will iteratively find all the anti-podal points of the polygon. A pair of anti-podal points is defined a pair of points through which two parallel tangents can be drawn to the polygon each of which does not intersect any other edge of the polygon. We can generate all the antipodal points by first determining one pair and then rotating the tangents minimally along the sides of the polygon about one of the points of this anti-podal pair till they pass another set of antipodal points. In our algorithm, we can find our first anti-podal pair as the pair of points, first of which has the minimum y co-ordinate and the other the maximum y co-ordinate amongst the set of vertices of the polygon. We stop iterating when the total angle by which we have rotated the parallel lines becomes  $\geq \pi$  because at this stage, we are back at the first anti-podal pair and each of the tangents will now iterate over points that have been iterated over by the other tangent. Let's assume two methods  $angle(line_a, line_b)$  that returns the angle between lines  $line_a$  and  $line_b$  and  $distance(point_a, point_b)$  that returns the distance between points  $point_a$  and  $point_b$ . The anti-podal pair with the maximum distance between them is our required pair. If there are many such pairs, we return the first one to be found.

Here is the pseudo-code:

```

n ← number of vertices
p1 ← point with minimum y-co-ordinate
p2 ... pn ← points sorted CCW according to polar angle from p1 ... (1)
pa ← p1
pb ← point with maximum y-co-ordinate
angleRotated ← 0
maxDistance ← distance(pa, pb)
furthermostPair ← (pa, pb)
supportingLinea ← horizontal vector passing thro' pa towards +ve X axis
supportingLineb ← horizontal vector passing thro' pb towards -ve X axis
while angleRotated < π do
    edgea ← edge(pa, pa+1) (This index wraps around. pn+1 = p1)
    edgeb ← edge(pb, pb+1)
    anglea ← angle(supportingLinea, edgea)
    angleb ← angle(supportingLineb, edgeb)
    if anglea < angleb then
        if distance(pa+1, pb) > maxDistance then
            maxDistance ← distance(pa+1, pb)
            furthermostPair ← (pa+1, pb)
        end if
        pa ← pa+1
    else if angleb < anglea then

```

```

if  $distance(p_a, p_{b+1}) > maxDistance$  then
     $maxDistance \leftarrow distance(p_a, p_{b+1})$ 
     $furthermostPair \leftarrow (p_a, p_{b+1})$ 
end if
 $p_b \leftarrow p_{b+1}$ 
else (i.e.  $angle_a = angle_b$ )
    if  $distance(p_{a+1}, p_b) > maxDistance$  then
         $maxDistance \leftarrow distance(p_{a+1}, p_b)$ 
         $furthermostPair \leftarrow (p_{a+1}, p_b)$ 
    else if  $distance(p_a, p_{b+1}) > maxDistance$  then
         $maxDistance \leftarrow distance(p_a, p_{b+1})$ 
         $furthermostPair \leftarrow (p_a, p_{b+1})$ 
    else if  $distance(p_{a+1}, p_{b+1}) > maxDistance$  then
         $maxDistance \leftarrow distance(p_{a+1}, p_{b+1})$ 
         $furthermostPair \leftarrow (p_{a+1}, p_{b+1})$ 
    end if
     $p_a \leftarrow p_{a+1}$ 
     $p_b \leftarrow p_{b+1}$  (This indices wrap around.  $p_{n+1} = p_1$ )
end if
 $angleRotated \leftarrow angleRotated + \min(angle_a, angle_b)$ 
end while
return  $furthermostPair$ 

```

This algorithm works in  $\mathcal{O}(n \lg n)$  time. Let's analyze why. There are two main tasks in this algorithm:

- Sorting vertices in CCW order from  $p_1$
- Iterating through the vertices optimally to determine the pair furthest apart

We know that sorting vertices in CCW order from  $p_1$  takes  $\mathcal{O}(n \lg n)$  time. Inspecting the above algorithm, we see that we by since  $angleRotated$  starts from 0 and ends at  $\pi$ , we can conclude that the two point variables,  $p_a$  and  $p_b$  iterate over every point at most once (except for the initial anti-podal pair which will also be the last pair we inspect before terminating). Therefore, the number of iterations is  $\mathcal{O}(n)$ .

Therefore the total running time of the algorithm =  $\mathcal{O}(n \lg n) + \mathcal{O}(n) = \mathcal{O}(n \lg n)$



## b Checking if two convex hulls intersect

Two convex hulls intersect if any one of the vertices of the first one lies strictly inside the other one. To do this, we first need to find which of the polygons is on the right of the other. We can do this by calculating their centroid (avg. of the x co-ordinates, avg. of the y co-ordinates). For the purposes of the pseudocode, let's assume the hull with  $m$  vertices is on the right. For each vertex for the left hull, we see if it lies inside the right hull. To see if a point lies inside a polygon, we draw a horizontal line from the vertex to just outside the right hull. We count the number of edges of the right hull this horizontal intersects. This will be either 1 or 2 because both are convex hulls. If it is = 2, then the vertex is outside the right hull, otherwise it's inside. Here is the pseudo code.

```

function CHECKPOLYGONINTERSECTION(ConvexHull A, ConvexHull B)
   $P \leftarrow$  convex hull to the left.
   $Q \leftarrow$  convex hull to the right.
   $p_{1...n} \leftarrow$  points on  $P$ 
   $q_{1...m} \leftarrow$  points on  $Q$ 
   $rightmostX \leftarrow$  the X co-ordinate of the point on  $Q$  with the maximum X
  co-ordinate
  for all  $p$  in  $p_{1...n}$  do
    if  $isPointInPolygon(Q, p, rightmostX)$  then
      return true
    end if
  end for
  return false                                 $\triangleright$  None of the points in P are inside Q
end function

function ISPOINTINPOLYGON(Polygon Q, Point p, double maxCoordiante)
   $maxCoordiante$  is the X co-ordinate of the point in Q
  which has the max X Co-ordinate (right most point)

   $horizontal = LineSegment(p, Point(maxCoordiante + 1, p_y))$   $\triangleright$  making
  sure that the end of  $horizontal$  is to the right of Q
   $q_{1...m} \leftarrow$  points on  $Q$ 
   $count \leftarrow 0$ 
  for all  $q_i$  in  $q_{1...n}$  do
     $edge = LineSegment(q_i, q_{i+1})$   $\triangleright$  indices wrap around,  $q_{m+1} = q_1$ 
    if  $isIntersecting(horizontal, edge)$  then
       $count \leftarrow count + 1$ 
    end if
  end for
  if  $count == 2$  then
    return false
  else
    return true
  end if

```

**end function**

**function** ISPOINTINPOLYGON(*LineSegment*  $L_1$ , *LineSegment*  $L_2$ )

$p_1 = (x_1, y_1) \leftarrow$  starting point of *LineSegment*  $L_1$

$p_2 = (x_2, y_2) \leftarrow$  ending point of *LineSegment*  $L_1$

$p_3 = (x_3, y_3) \leftarrow$  starting point of *LineSegment*  $L_2$

$p_4 = (x_4, y_4) \leftarrow$  ending point of *LineSegment*  $L_2$

**if**  $\neg[(x_2 \geq x_3) \wedge (x_4 \geq x_1)] \wedge [(y_2 \geq y_3) \wedge (y_4 \geq y_1)]$  **then**

**return** *false*    $\triangleright$  If bounding boxes don't intersect, lines can't either

**end if**

*Vector*  $v_1 = (p_2 - p_1)$

*Vector*  $v_2 = (p_3 - p_1)$

*Vector*  $v_3 = (p_4 - p_1)$

$product_1 \leftarrow v_2 \times v_1$

$product_2 \leftarrow v_3 \times v_1$

**if**  $product_1 \times product_2 \geq 0$  **then**

$\triangleright$  If  $product_1 \times product_2 = 0$ , one (or both)  $p_3$  and  $p_4$  is collinear with  $p_1$  and  $p_2$

$\triangleright$  If  $product_1 \times product_2 > 0$ , both  $product_1$  and  $product_2$  have the same sign, and thus the points fail the straddle test

**return** *false*

**end if**

changing the reference points (swapping roles) and doing the test again

$v_1 \leftarrow (p_3 - p_4)$

$v_2 \leftarrow (p_1 - p_3)$

$v_3 \leftarrow (p_2 - p_3)$

$product_1 \leftarrow v_2 \times v_1$

$product_2 \leftarrow v_3 \times v_1$

**if**  $product_1 \times product_2 \geq 0$  **then**

$\triangleright$  If  $product_1 \times product_2 = 0$ , one (or both)  $p_3$  and  $p_4$  is collinear with  $p_1$  and  $p_2$

$\triangleright$  If  $product_1 \times product_2 > 0$ , both  $product_1$  and  $product_2$  have the same sign, and thus the points fail the straddle test

**return** *false*

**end if**

**return** *true*    $\triangleright$  the points passed the rejection test and the two straddle tests, therefore they are strictly intersecting

**end function**

This algorithm works in  $\Theta(mn)$  time. Let's analyze why. These are main tasks in this algorithm:

- Finding which hull is to the right. ( $\Theta(n + m)$ )
- Finding the right-most point of the right hull. ( $\Theta(m)$ )
- Iterating through the vertices of the left hull and seeing if the vertex lies inside the the right hull

Inspecting the above algorithm, we see that to find if a point is lying inside a polygon of  $m$  sides, takes  $\Theta(m)$  time because we iterate over all its  $m$  edges once. We do this for each of the  $n$  vertices of the left hull, taking  $\Theta(m)$  each time, totally taking  $n * \Theta(m) = \Theta(mn)$  time. Therefore the total running time of the algorithm  $= \Theta(n + m) + \Theta(m) + \Theta(mn) = \Theta(mn)$

### c Nearest pair of vertices of two convex hulls

We shall use a slight modification of the rotating-callipers algorithm to find our answer. We will iteratively find all the anti-podal points between the polygons. A pair of anti-podal points between two convex polygons is defined a pair of points (one from each polygon) through which a pair of anti-parallel tangents can be drawn to the respective polygons which does not intersect any other edge of that polygon. We can generate all the antipodal points by first determining one pair and then rotating the tangents minimally along the sides of the polygon till they pass another set of antipodal points. In our algorithm, we can find our first anti-podal pair as the pair of points, first of which has the minimum y co-ordinate amongst the points of the first hull and the other the maximum y co-ordinate amongst the set of points in the other hull. We stop iterating when the total angle by which the tangents have been rotated  $\geq 2\pi$  because at this stage, all points of both the convex hulls have been iterated over by the respective turning tangent. Let's assume two methods  $angle(line_a, line_b)$  that returns the angle between lines  $line_a$  and  $line_b$  and  $distance(point_a, point_b)$  that returns the distance between points  $point_a$  and  $point_b$ . The anti-podal pair with the minimum distance between them is our required pair. If there are many such pairs, we return the first one to be found.

Here is the pseudo-code:

```

 $n \leftarrow$  number of vertices in  $P$ 
 $m \leftarrow$  number of vertices in  $Q$ 
 $p_1 \leftarrow$  point in  $P$  with minimum y-co-ordinate
 $p_2 \dots p_n \leftarrow$  points sorted CCW according to polar angle from  $p_1$ 
 $q_1 \leftarrow$  point in  $Q$  with maximum y-co-ordinate
 $q_2 \dots q_m \leftarrow$  points sorted CCW according to polar angle from  $q_1$ 
 $p_a \leftarrow p_1$ 
 $q_b \leftarrow q_1$ 
 $angleRotated \leftarrow 0$ 
 $minDistance \leftarrow distance(p_a, q_b)$ 
 $nearestPair \leftarrow (p_a, q_b)$ 
 $supportingLine_a \leftarrow$  horizontal vector passing thro'  $p_a$  towards +ve X axis
 $supportingLine_b \leftarrow$  horizontal vector passing thro'  $q_b$  towards -ve X axis
while  $angleRotated < 2\pi$  do
     $edge_a \leftarrow edge(p_a, p_{a+1})$  (This index wraps around.  $p_{n+1} = p_1$ )
     $edge_b \leftarrow edge(q_b, q_{b+1})$  (This index wraps around.  $q_{m+1} = q_1$ )
     $angle_a \leftarrow angle(supportingLine_a, edge_a)$ 
     $angle_b \leftarrow angle(supportingLine_b, edge_b)$ 
    if  $angle_a < angle_b$  then
        if  $distance(p_{a+1}, q_b) < minDistance$  then
             $minDistance \leftarrow distance(p_{a+1}, q_b)$ 
             $nearestPair \leftarrow (p_{a+1}, q_b)$ 
        end if
     $p_a \leftarrow p_{a+1}$ 

```

```

else if  $angle_b < angle_a$  then
  if  $distance(p_a, q_{b+1}) < minDistance$  then
     $minDistance \leftarrow distance(p_a, q_{b+1})$ 
     $nearestPair \leftarrow (p_a, q_{b+1})$ 
  end if
   $p_b \leftarrow q_{b+1}$ 
else (i.e.  $angle_a = angle_b$ )
  if  $distance(p_{a+1}, q_b) < minDistance$  then
     $minDistance \leftarrow distance(p_{a+1}, q_b)$ 
     $nearestPair \leftarrow (p_{a+1}, q_b)$ 
  else if  $distance(p_a, p_{b+1}) < minDistance$  then
     $minDistance \leftarrow distance(p_a, p_{b+1})$ 
     $nearestPair \leftarrow (p_a, p_{b+1})$ 
  else if  $distance(p_{a+1}, p_{b+1}) < minDistance$  then
     $minDistance \leftarrow distance(p_{a+1}, p_{b+1})$ 
     $nearestPair \leftarrow (p_{a+1}, p_{b+1})$ 
  end if
   $p_a \leftarrow p_{a+1}$ 
   $q_b \leftarrow q_{b+1}$ 
end if
   $angleRotated \leftarrow angleRotated + \min(angle_a, angle_b)$ 
end while
return  $nearestPair$ 

```

This algorithm works in  $\mathcal{O}(n \lg n)$  time. Let's analyze why. There are two main tasks in this algorithm:

- Sorting vertices of P in CCW order from  $p_1$ .  $\mathcal{O}(n \lg n)$
- Sorting vertices of Q in CCW order from  $q_1$ .  $\mathcal{O}(m \lg m)$
- Iterating through the vertices optimally to determine the nearest

Inspecting the above algorithm, we see that we by since  $angleRotated$  starts from 0 and ends at  $2\pi$ , we can conclude that the two point variables,  $p_a$  and  $q_b$  iterate over each vertex of their respective polygons at most once. Therefore, the number of iterations is  $\mathcal{O}(n + m)$ .

Therefore the total running time of the algorithm =  $\mathcal{O}(n \lg n) + \mathcal{O}(m \lg m) + \mathcal{O}(n + m) = \mathcal{O}(n \lg n)$  (for asymptotic upper bound)

### 3 Question 3

a

```
int fib1(n)
{
    if (n==0||n==1)
        return Soln[n];
    Soln[n-1] = fib1(n-1);
    If (Soln[n-2] == infinity)
        Soln[n-2] = fib(n-2);
    Soln[n] = Soln[n-1] + Soln[n-2];
    return Soln[n];
}
```

Let  $T(n)$  be the time required to compute  $\text{fib1}(n)$ .

Observations :

If  $n \geq 2$ , the recursive call  $\text{fib1}(n-1)$  is called. That in turn computes  $\text{Soln}[n-2]$ , so  $\text{Soln}[n-2]$  will never be  $\infty$  and the statement  $\text{Soln}[n-2] = \text{fib}(n-2)$  is never executed and can be ignored for our calculation.

Therefore,

$$\begin{aligned} T(0) &= \Theta(1) \\ T(1) &= \Theta(1) \\ T(n) &= T(n-1) + \Theta(1) \\ &= T(n-2) + \Theta(1) + \Theta(1) \\ &\vdots \\ &= T(n-k) + k\Theta(1) \end{aligned}$$

taking  $n = k$ ,

$$\begin{aligned} &= T(0) + n\Theta(1) \\ &= \Theta(n) \\ T(n) &= \Theta(n) \end{aligned}$$

**Space complexity** is  $\mathcal{O}(n)$  because intermediate values are stored in an array of size  $n$ .

**Correctness** : This algorithm first recursively calculates the value of  $\text{fib1}(n-1)$  which leads to a call trace which results in the calculation and storage of all the  $\text{Soln}[i]$  values from 2 to  $n-1$ . Then the other condition, if  $(\text{Soln} == \infty)$  never being true. Each  $\text{Soln}[i]$  value has been calculated and is correct because it = sum of  $\text{Soln}[i-1]$  and  $\text{Soln}[i-2]$ .

**b**

```
int fib2 (n)
{
    if (n==0||n==1)
        return Soln [n];
    Soln [n-2] = fib2 (n-2);
    Soln [n-1] = fib2 (n-1);
    return (Soln [n-1]+Soln [n-2]);
}
```

Let  $T(n)$  be the time required to compute  $\text{fib2}(n)$ .  
Observations :

$$\begin{aligned}T(0) &= \Theta(1) \\T(1) &= \Theta(1) \\T(n) &= T(n-1) + T(n-2) + 1\end{aligned}$$

Here let the time taken for all the arithmetic operations in the function be 1 unit

Now, by substitution, no polynomial function  $n^c$  will balance the equation, (where  $c$  is a constant).

Hence we try an exponential function.  $c^n$ , like  $T(n) = c^n$

$$T(n) = T(n-1) + T(n-2) + 1$$

This equation will be easier to work with if we eliminate the constant 1 unit.  
Trying,  $T(n) = c^n - 1$

$$\begin{aligned}T(n) &= T(n-1) + T(n-2) + 1 \\c^n - 1 &= (c^{n-1} - 1) + (c^{n-2} - 1) + 1 \\c^n &= c^{n-1} + c^{n-2} \\\Rightarrow c^2 - c - 1 &= 0 \\\Rightarrow c &= \frac{1 \pm \sqrt{5}}{2}\end{aligned}$$

Therefore,

$$\begin{aligned}T(n) &= \Theta(c^n) \\&= \Theta\left(\left(\frac{1 + \sqrt{5}}{2}\right)^n\right)\end{aligned}$$

**Space complexity** is  $\mathcal{O}(n)$  because intermediate values are stored in an array of size  $n$ .

**Correctness** : For each  $\text{fib2}(n)$  calculation, this algorithm recursively computes and saves  $\text{fib2}(n-1)$  and  $\text{fib2}(n-2)$  and saves them in  $\text{Soln}[n-1]$  and  $\text{Soln}[n-2]$  respectively before returning their sum. So though this method is more complex than the others in the question and re-computes all the intermediate values and doesn't make full use of memorization for optimization, it is correct.



**c**

```
int fib3(n)
{
    if (n==0||n==1)
        return Soln[n];
    Soln[n-1] = fib3(n-1);
    Soln[n] = Soln[n-1]+Soln[n-2];
    return Soln[n];
}
```

Let  $T(n)$  be the time required to compute  $\text{fib3}(n)$ .  
Observations :

$$\begin{aligned}T(0) &= \Theta(1) \\T(1) &= \Theta(1) \\T(n) &= T(n-1) + \Theta(1) \\&= T(n-2) + \Theta(1) + \Theta(1) \\&\vdots \\&= T(n-k) + k\Theta(1)\end{aligned}$$

taking  $n = k$ ,

$$\begin{aligned}&= T(0) + n\Theta(1) \\&= \Theta(n) \\T(n) &= \Theta(n)\end{aligned}$$

**Space complexity** is  $\mathcal{O}(n)$  because intermediate values are stored in an array of size  $n$ .

**Correctness** : This algorithm first tries to compute the  $\text{fib3}(n-1)$  and saves that in  $\text{Soln}[n]$ . This calculation involves recursively calling  $\text{fib3}(n-1)$  till  $\text{fib3}(1)$  which is known. Thereafter all the consecutive  $\text{Soln}[i]$  values are computed =  $\text{Soln}[i-1] + \text{Soln}[i-2]$  till  $\text{Soln}[n-1]$ . After which  $\text{Soln}[n] = \text{Soln}[n-1] + \text{Soln}[n-2]$  is computed and returned. This is the correct value for  $\text{fib3}(n)$ .

**d**

```
int fib4(n)
{
    if (n==0||n==1)
        return Soln[n];
    Soln[n-1] = fib4(n-1);
    return Soln[n-1] + Soln[n-2];
}
```

Let  $T(n)$  be the time required to compute  $\text{fib4}(n)$ .  
Observations :

$$\begin{aligned}T(0) &= \Theta(1) \\T(1) &= \Theta(1) \\T(n) &= T(n-1) + \Theta(1) \\&= T(n-2) + \Theta(1) + \Theta(1) \\&\vdots \\&= T(n-k) + k\Theta(1)\end{aligned}$$

taking  $n = k$ ,

$$\begin{aligned}&= T(0) + n\Theta(1) \\&= \Theta(n) \\T(n) &= \Theta(n)\end{aligned}$$

**Space complexity** is  $\mathcal{O}(n)$  because intermediate values are stored in an array of size  $n$ .

**Correctness** : This algorithm first tries to compute the  $\text{fib4}(n-1)$  and saves that in  $\text{Soln}[n-1]$ . This calculation involves recursively calling  $\text{fib4}(n-1)$  till  $\text{fib4}(1)$  which is known. Thereafter all the consecutive  $\text{Soln}[i]$  values are computed till  $\text{Sol}[n-1]$ . After which  $\text{Soln}[n-1] + \text{Soln}[n-2]$  is computed and returned. This is the correct value for  $\text{fib4}(n)$ .

## 4 Question 4

### a Finding maximum flow over an arbitrary n-source m-sink network

We transform the problem into the problem of maximizing flow in 1-source 1-sink network by adding a super source leading to each of the  $n$  sources and a super sink to which each of the  $m$  sinks lead. If  $n$  is 1 or  $m$  is 1 then the respective super element need not be added. Each of these additional connections will have infinite capacity.

We will use a refinement of the Ford-Fulkerson algorithm called the Edmonds-Karp Algorithm which uses Breadth-First Search to choose the augmenting path with the smallest number of edges.

The data structures we need are as follows:-

- Capacity Matrix,  $G[V][V]$ , where  $V$  = number of vertices, containing the capacity of the various nodes.
- Flow Matrix  $f[V][V]$  containing the status of flow in the current state of the Graph.
- $S$ , and  $T$ , the indices of the super-source and super-sink respectively.
- A path between points is represented as an array containing indices of the nodes of the path.

**function** EDMUNDS-KARP(*CapacityMatrix*  $G$ )

    construct an empty flow matrix  $f$

**while**  $G$  contains a path from  $s$  to  $t$  **do**

$P \leftarrow s - t$  path in  $G$  with the minimum number of edges.

        Augment the flow with  $P$

        Update  $f$

        Update  $G$

**end while**

**end function**

**Analysis:**

- Adding a super source and super destination takes  $\mathcal{O}(n)$  and  $\mathcal{O}(m)$  time respectively because it takes  $\mathcal{O}(1)$  per node connected to the source or sink.  $\mathcal{O}(n) + \mathcal{O}(m)$  can be approximated to  $\mathcal{O}(V)$  because  $m + n \leq V$
- Using BFS to find a path (with available capacity) from  $s$  to  $t$  with the least number of nodes. Breadth first search in a graph with  $V$  vertices and  $E$  edges takes  $\mathcal{O}(V + E)$  time. Since every vertex is a part of at least one edge,  $V < E$  therefore, we can say approximate the time taken for the search is  $\mathcal{O}(E)$ .
- Number of augmentations is at most  $V \times E$  because the longest possible path can be of length  $V$  and in each augmentation, at least one of the  $E$

edges gets saturated. So in the worst case where the path of length  $V$ , in each iteration, one of the  $E$  edges will get saturated, so in total there will be  $VE$  augmentations. Therefore the theoretical maximum number of edges augmented is  $VE$  and the while loop runs at most  $VE$  times.

- The max flow is calculated by iterating over the  $m$ -sinks of the initial graph and seeing the flow in each of those nodes in the transformed graph. This can be done in  $\mathcal{O}(m)$  time and is approximated to  $\mathcal{O}(V)$  because  $m < V$ .

Therefore, the complexity of the algorithm is :

$$\begin{aligned} &= (VE)\mathcal{O}(E) + \mathcal{O}(V) + \mathcal{O}(V) \\ &= \mathcal{O}(VE^2) \end{aligned}$$

## **b Checking if flow is sustainable**

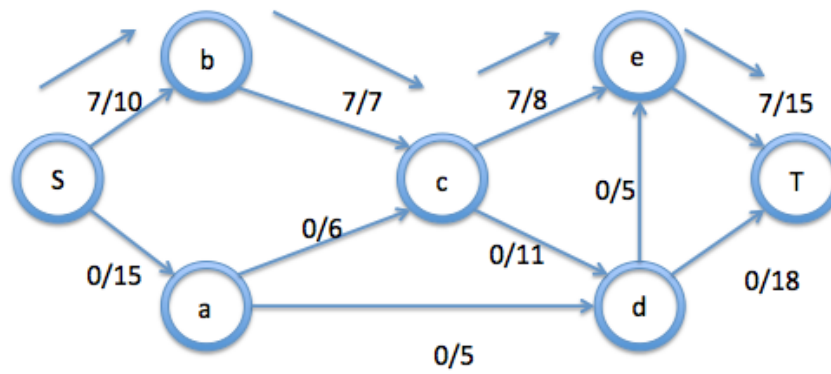
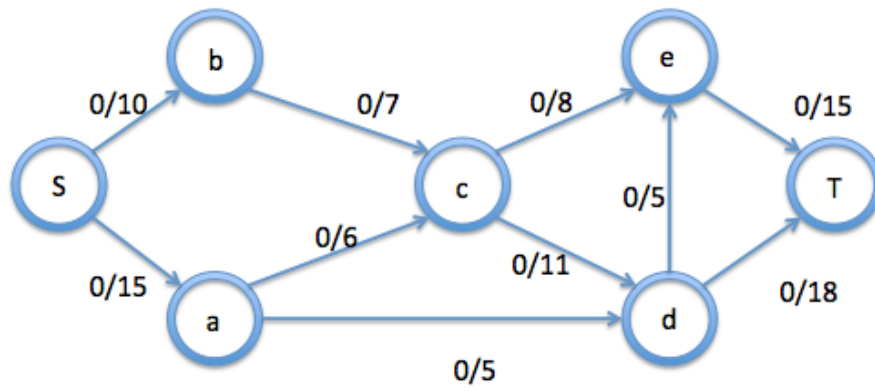
We do something similar to the previous problem by defining a super-source leading to all the sources and a super sink to which all the sinks lead. After that we find the maximum flow through this modified graph. If for this maximal flow, the outward flow from each original source node is  $\geq$  its production rate, then the network can sustain a flow where each source node meets its production requirement.

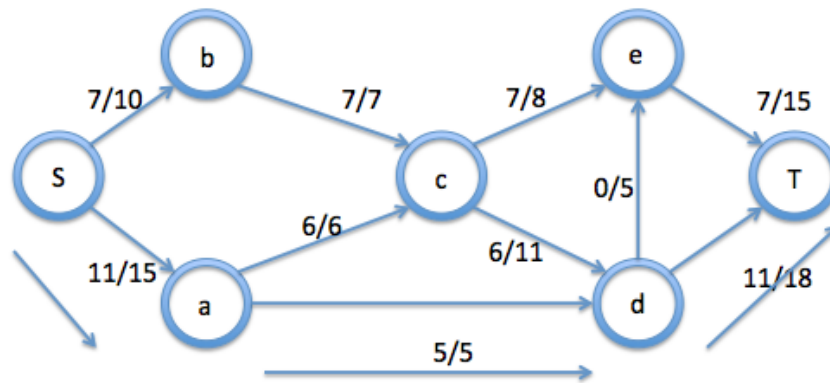
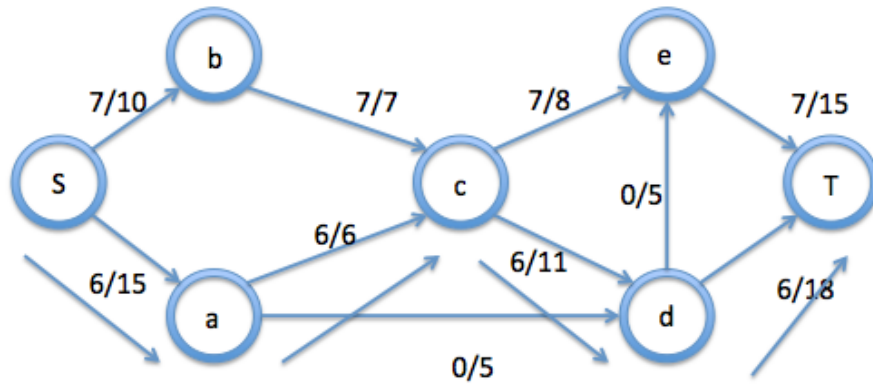
For this algorithm, the complexity can be calculated as follows. We know from the previous problem that for the maximal flow, the complexity is  $\mathcal{O}(VE^2)$ . The additional step in this algorithm is to check if in the maximal flow all source points have met their capacity. This can be done in  $\mathcal{O}(n)$  where  $n$  is the number of sources. This can be approximated to  $\mathcal{O}(V)$  because  $n < V$ .

Therefore, the complexity of this algorithm is :

$$\begin{aligned} &= \mathcal{O}(VE^2) + \mathcal{O}(V) \\ &= \mathcal{O}(VE^2) \end{aligned}$$

c Algorithm in action





Therefore, max flow = 18.

## References

- [1] <http://www.cs.cornell.edu/courses/cs4820/2010sp/handouts/edmondskarp.pdf>
- [2] <http://cgm.cs.mcgill.ca/~orm/rotcal.html>
- [3] <http://www.cs.uiuc.edu/class/sp07/cs473g/lectures/14-maxflowalgs.pdf>
- [4] [http://en.wikipedia.org/wiki/EdmondsKarp\\_algorithm/](http://en.wikipedia.org/wiki/EdmondsKarp_algorithm/)