

Introduction to

# Algorithm Design and Analysis

[15] Path in Graph

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# In the last class...

- Optimization Problem
  - Greedy strategy
- MST Problem
  - Prim algorithm
  - Kruskal algorithm
- Single-Source Shortest Path Problem
  - Dijkstra algorithm

# Path in Graph

- Single-source shortest paths (SSSP)
  - Dijkstra algorithm by example
  - Priority queue-based implementation
  - Proof of correctness
- All-pairs shortest paths (APSP)
  - Shortest path and transitive closure
  - Warshall algorithm for transitive closure
    - BF1, BF2, BF3 => Warshall algorithm
    - Floyd-Warshall algorithm for shortest paths

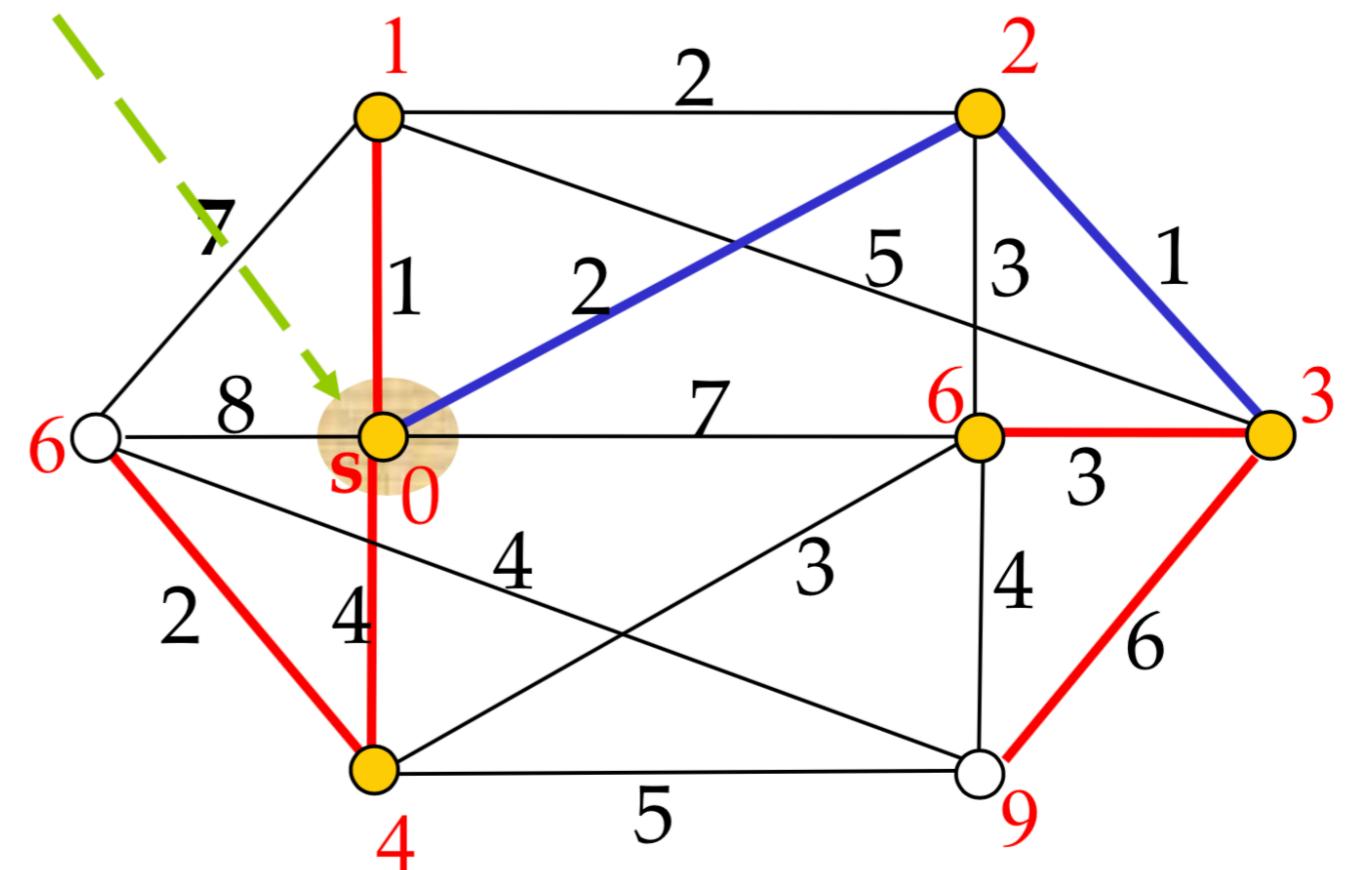
# Single Source Shortest Paths

The single source

Red labels on each vertex is the length of the shortest path from  $s$  to the vertex.

Note:

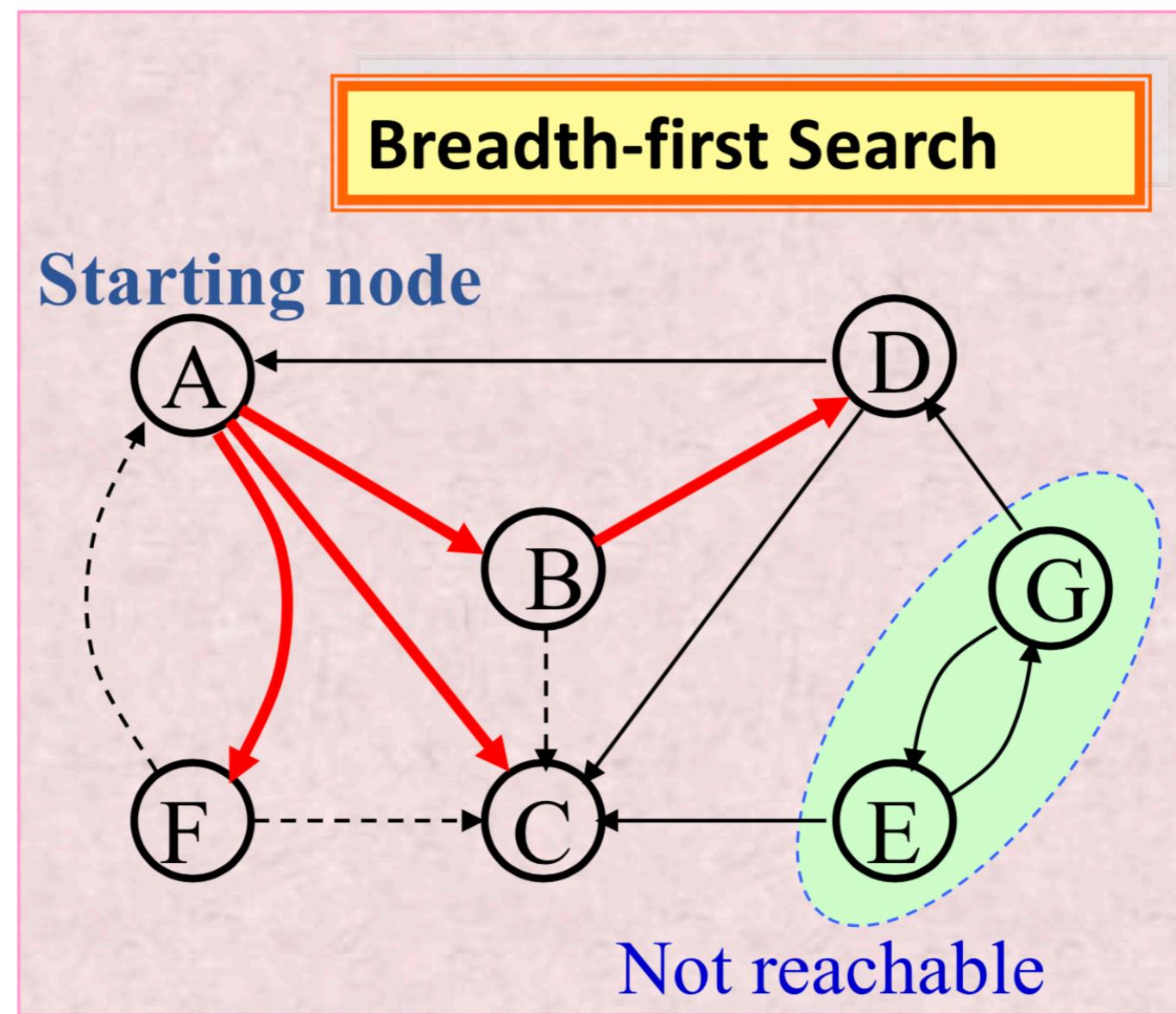
The shortest  $[0, 3]$ -path doesn't contain the shortest edge leaving  $s$ , the edge  $[0,1]$



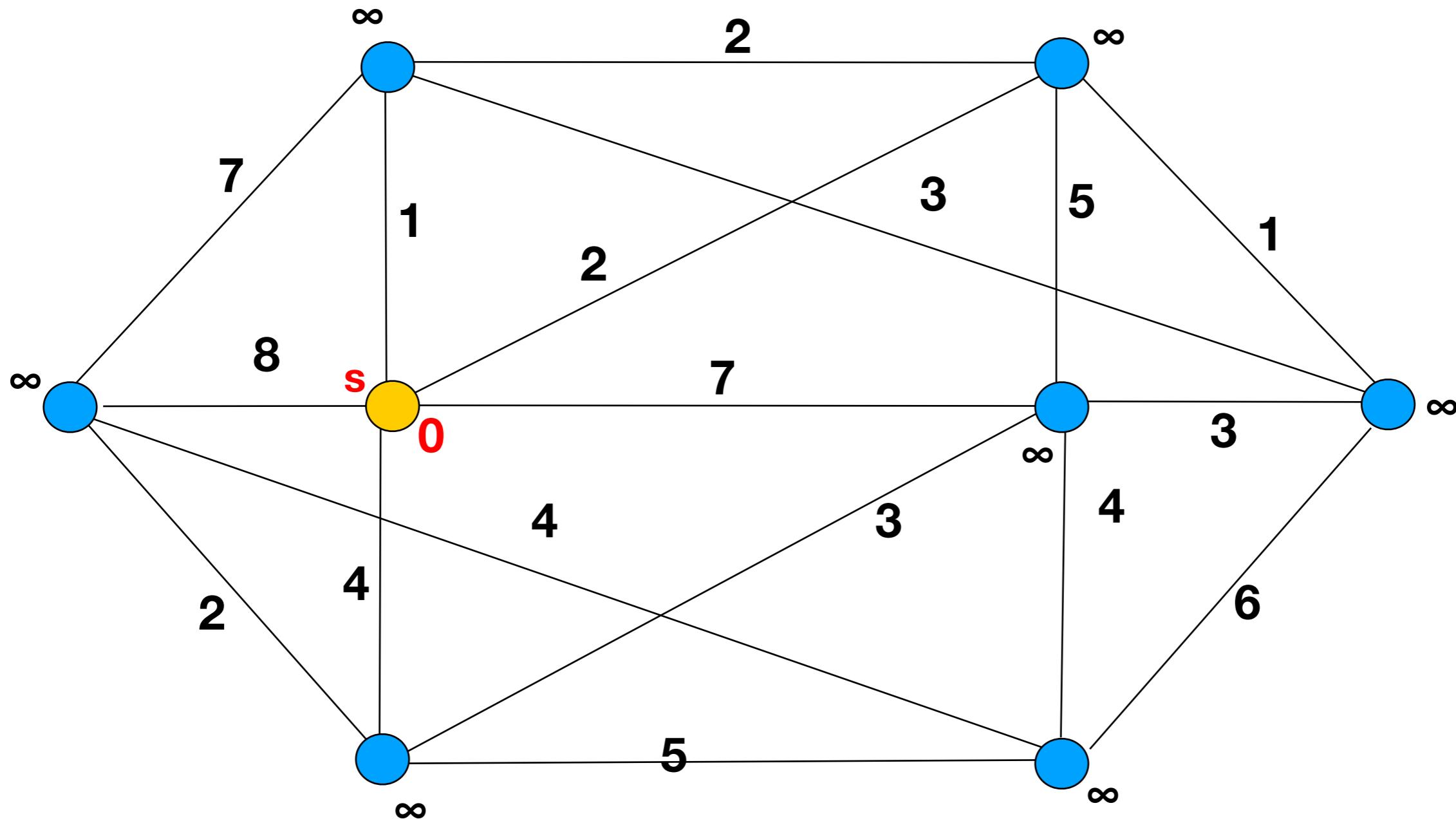
# Warm Up

- Single-source shortest path over uniformly weighted graph

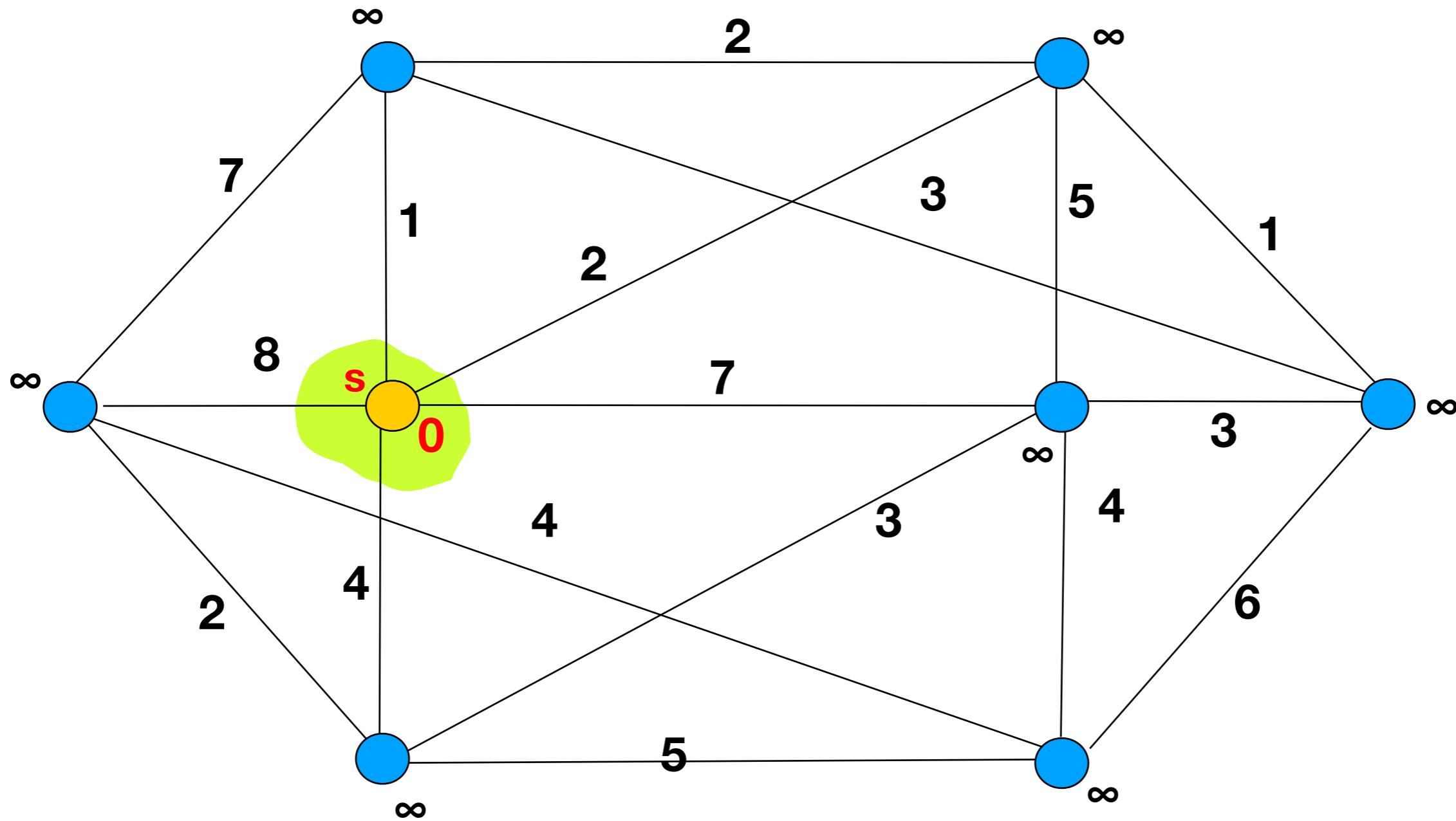
- Just BFS



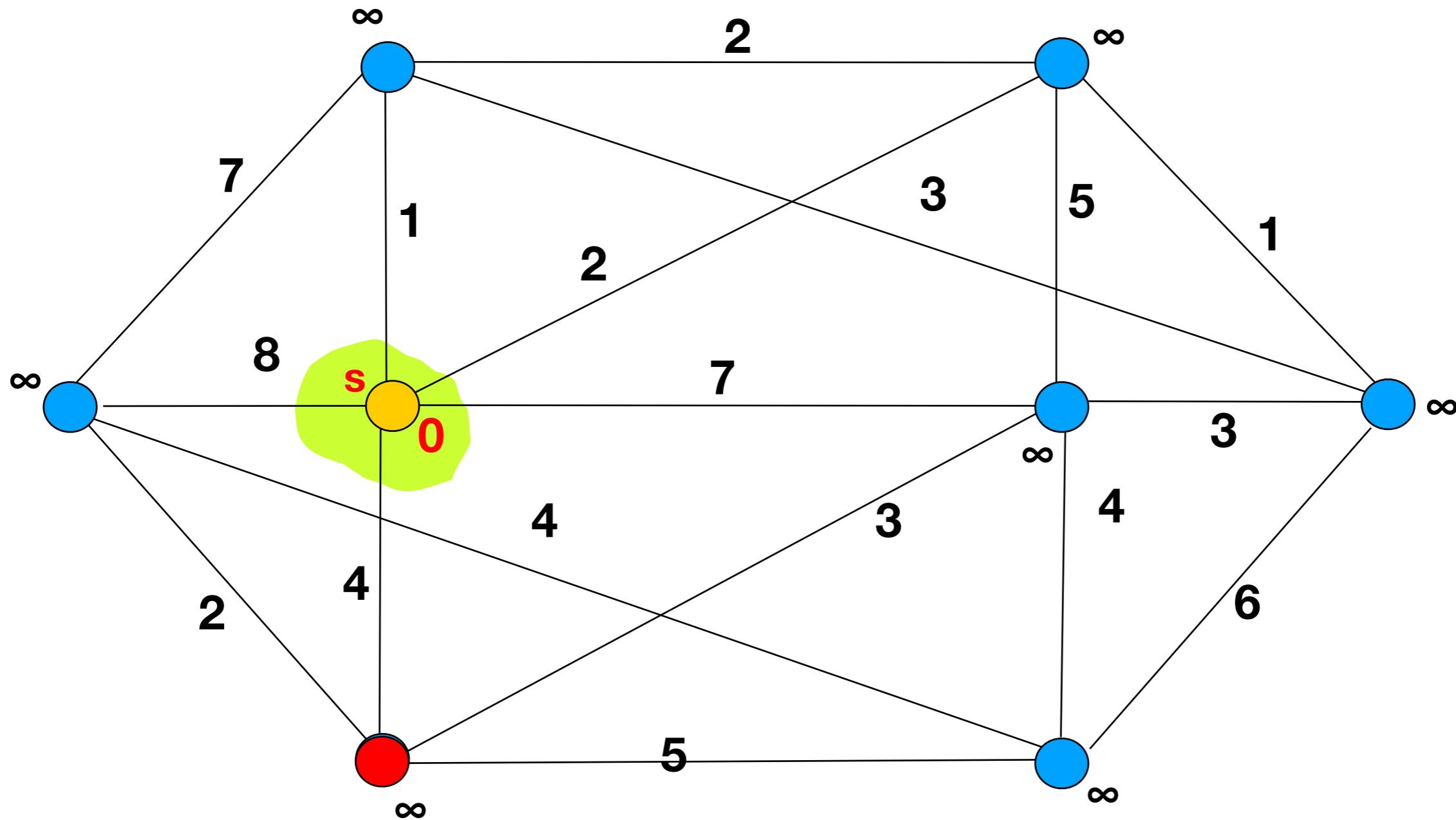
# Dijkstra's Algorithm



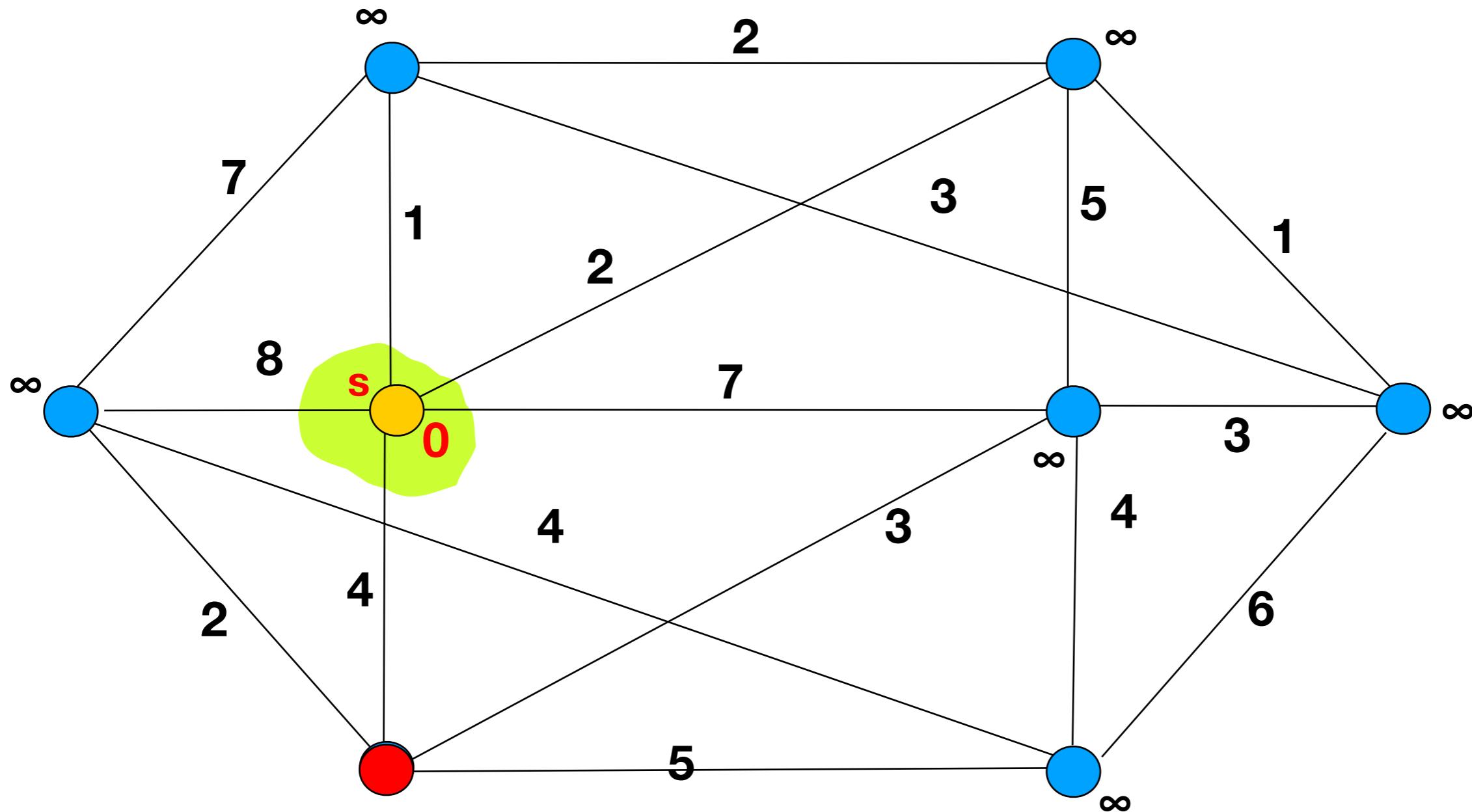
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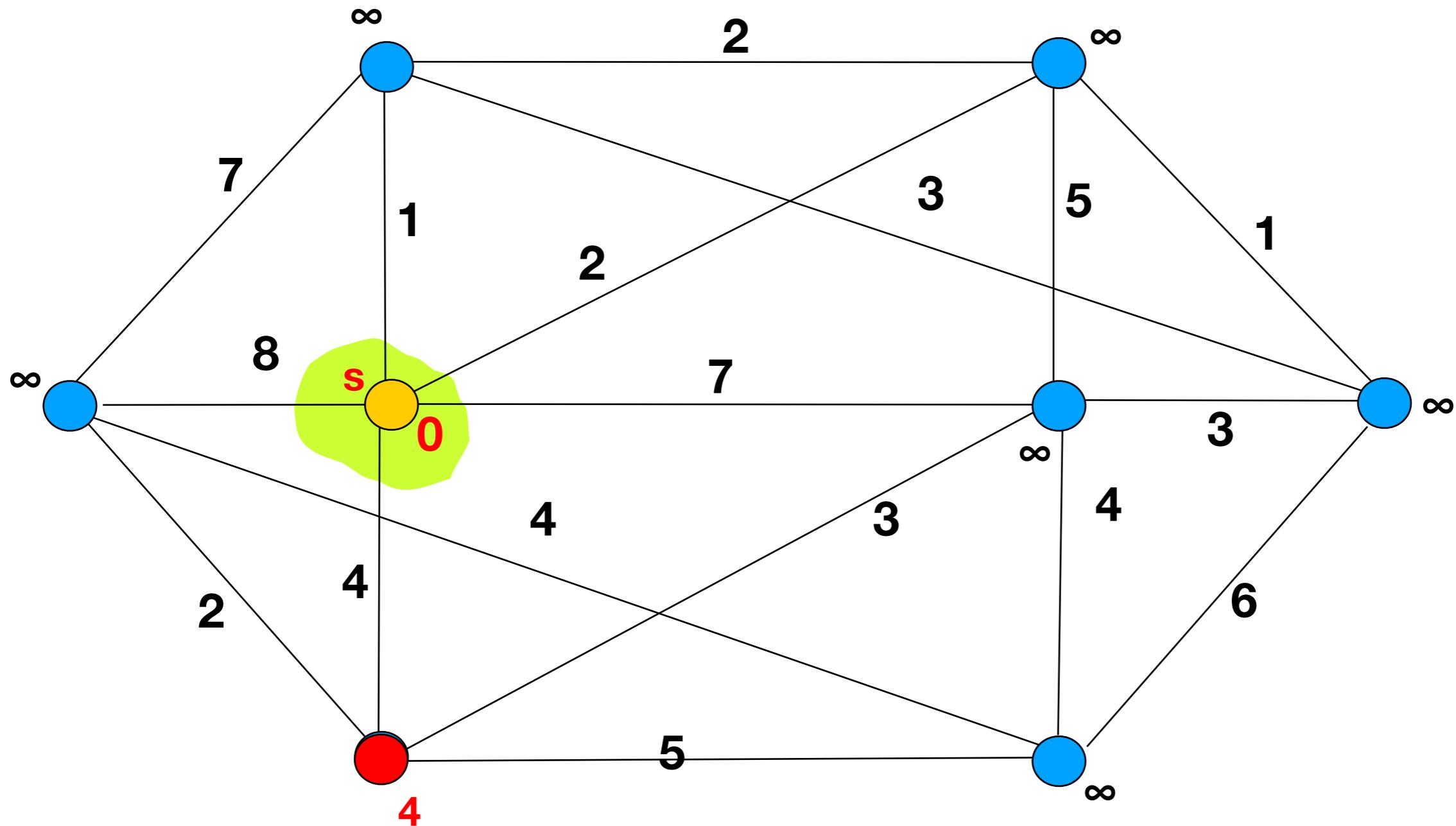
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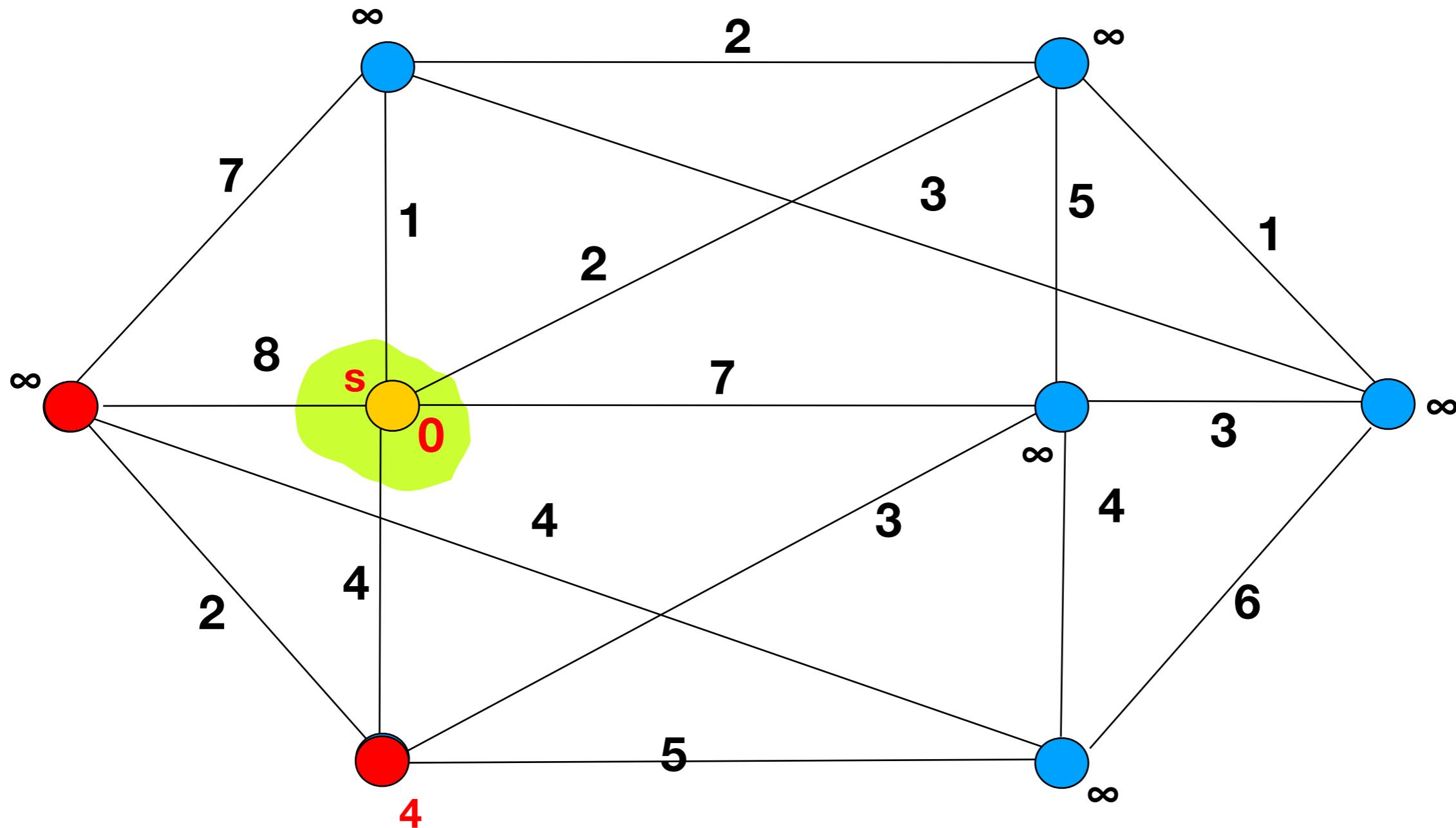
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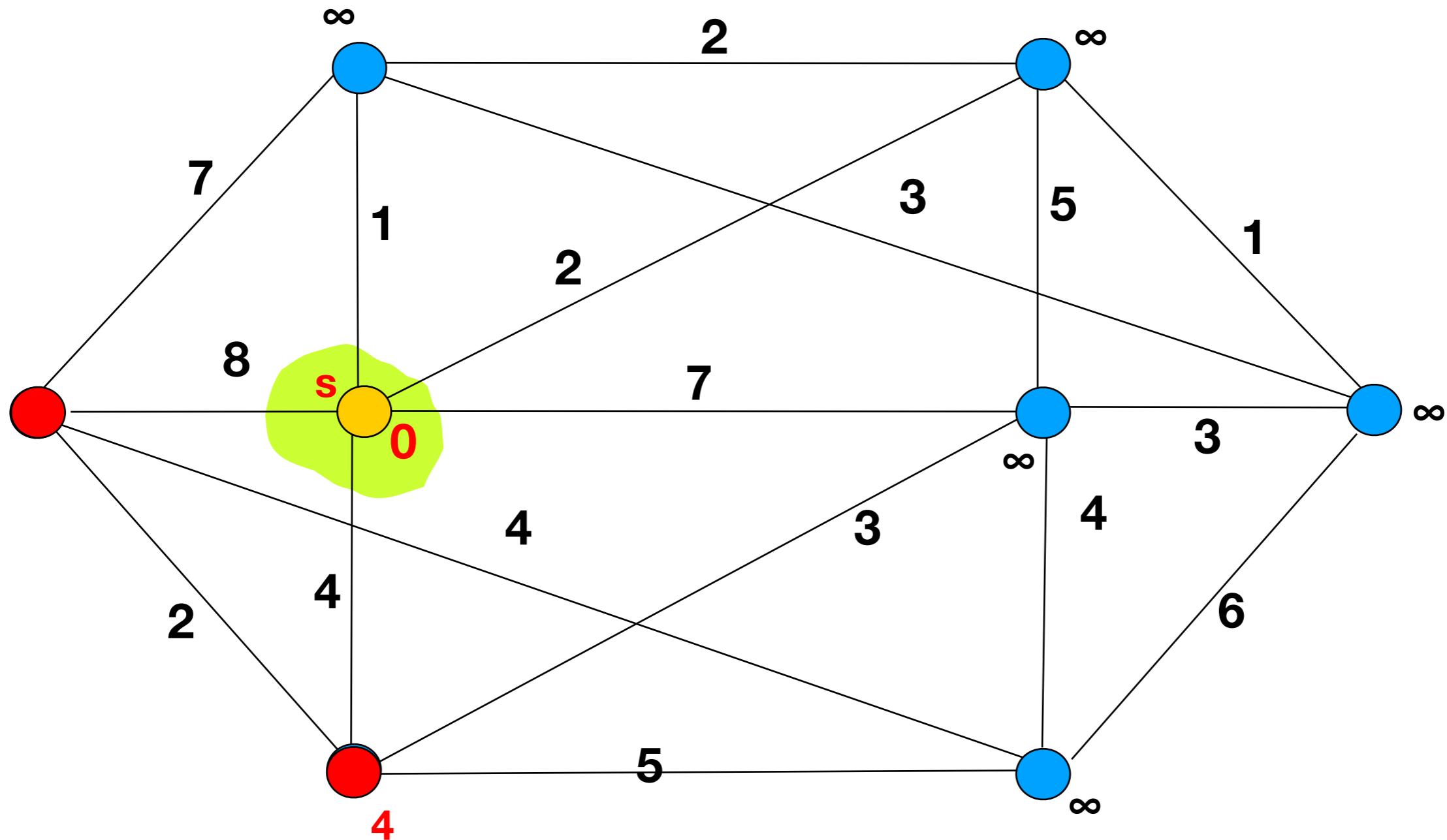
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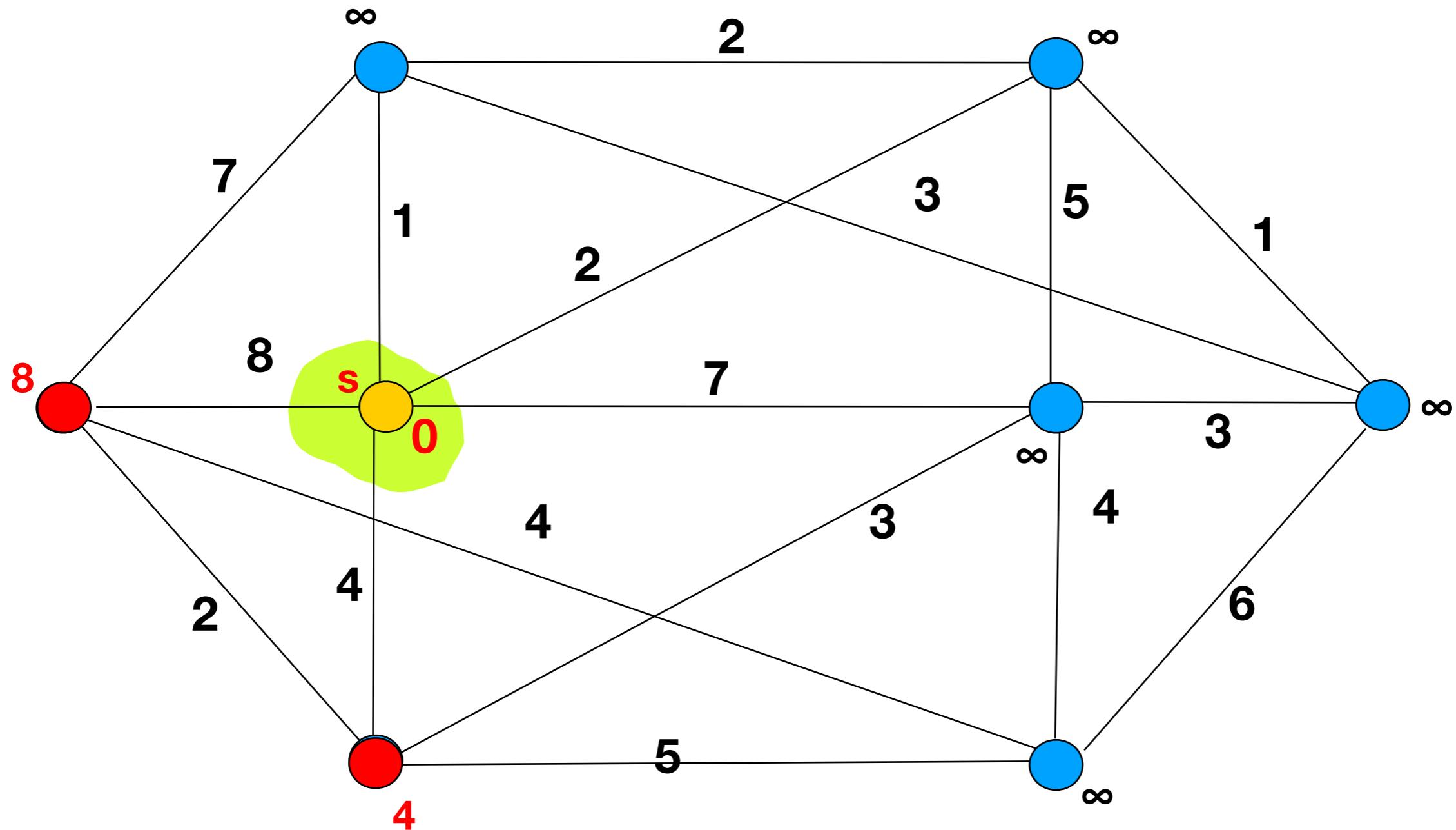
# Dijkstra's Algorithm



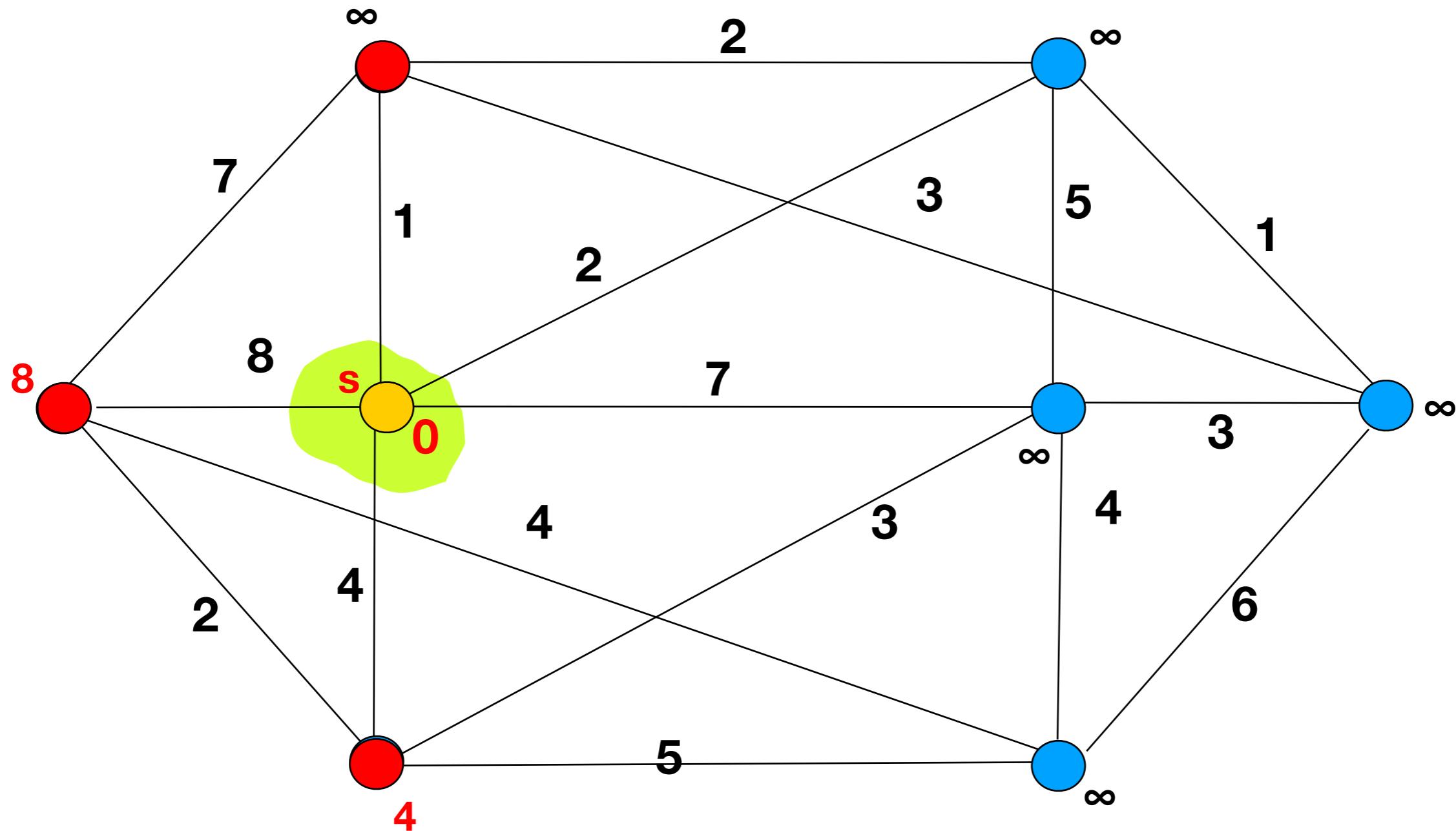
# Dijkstra's Algorithm



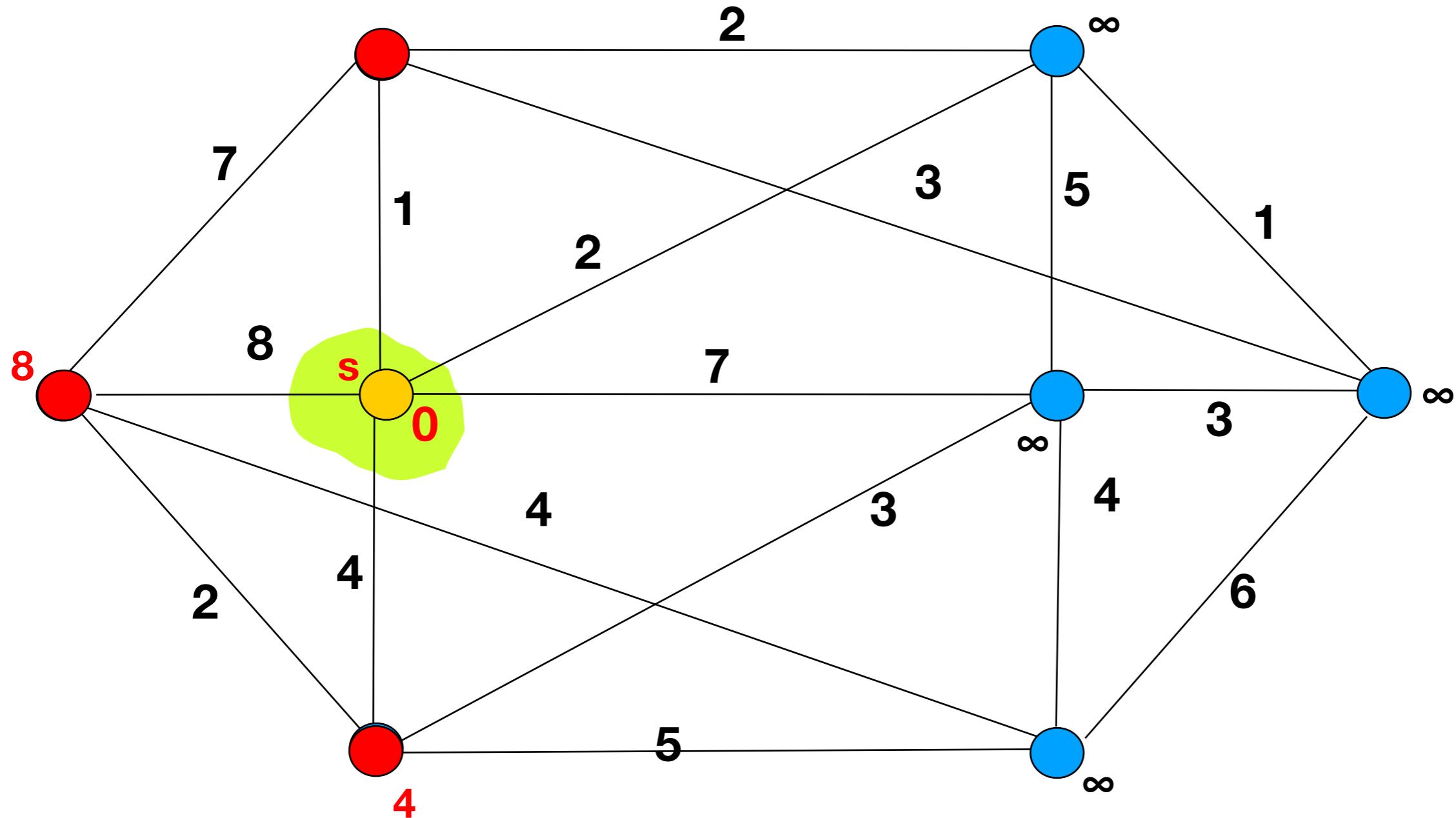
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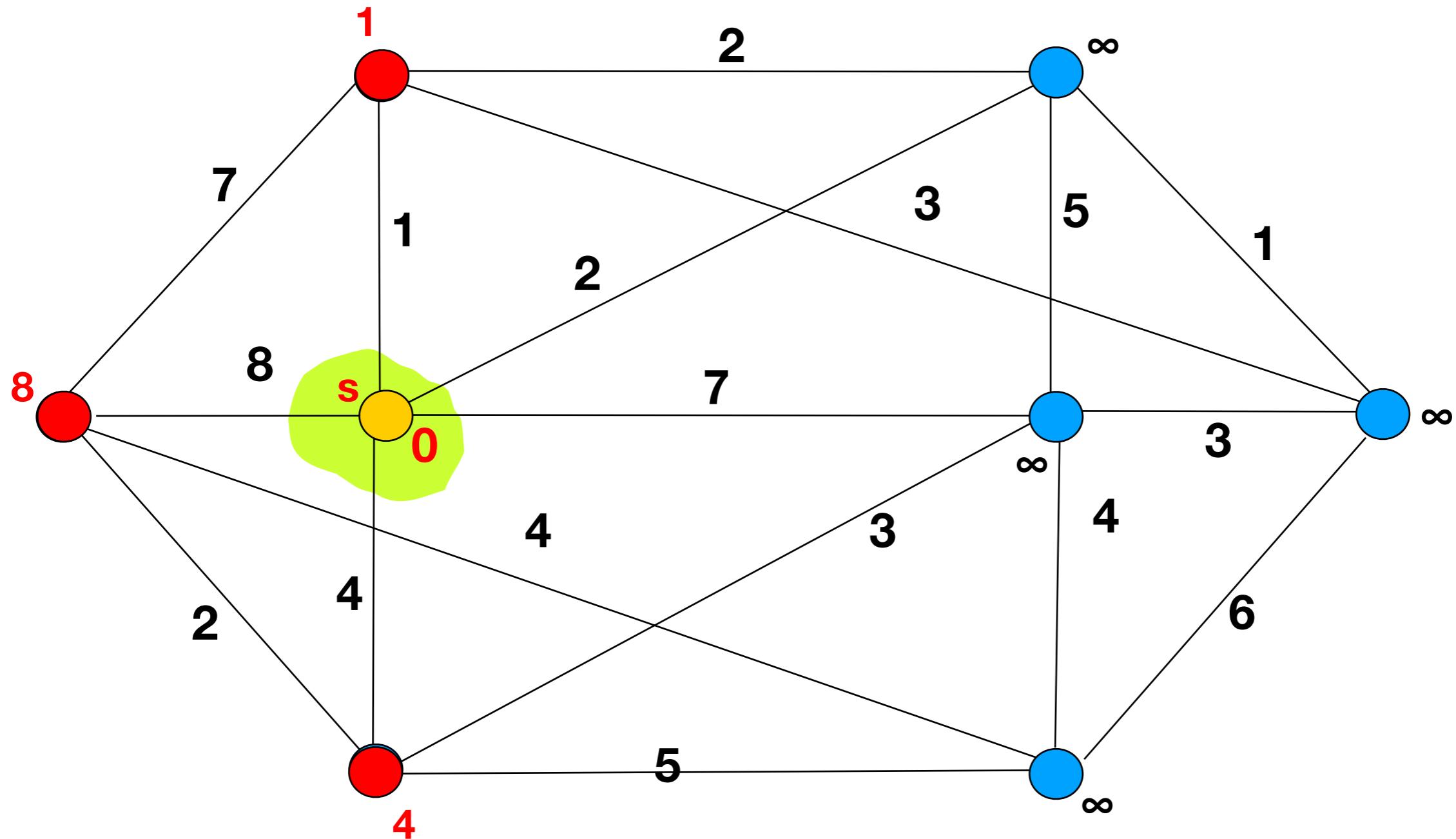
# Dijkstra's Algorithm



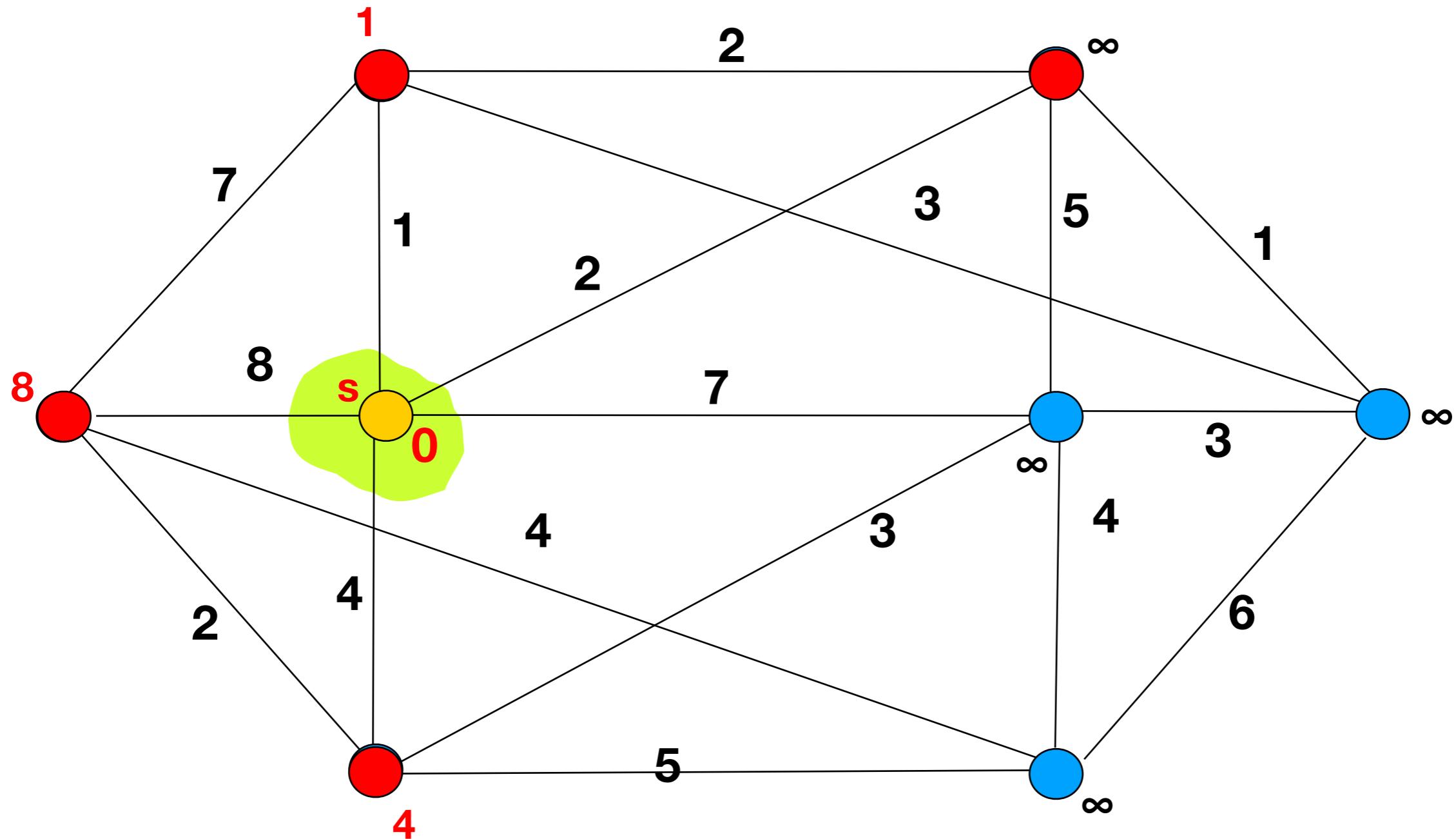
# Dijkstra's Algorithm



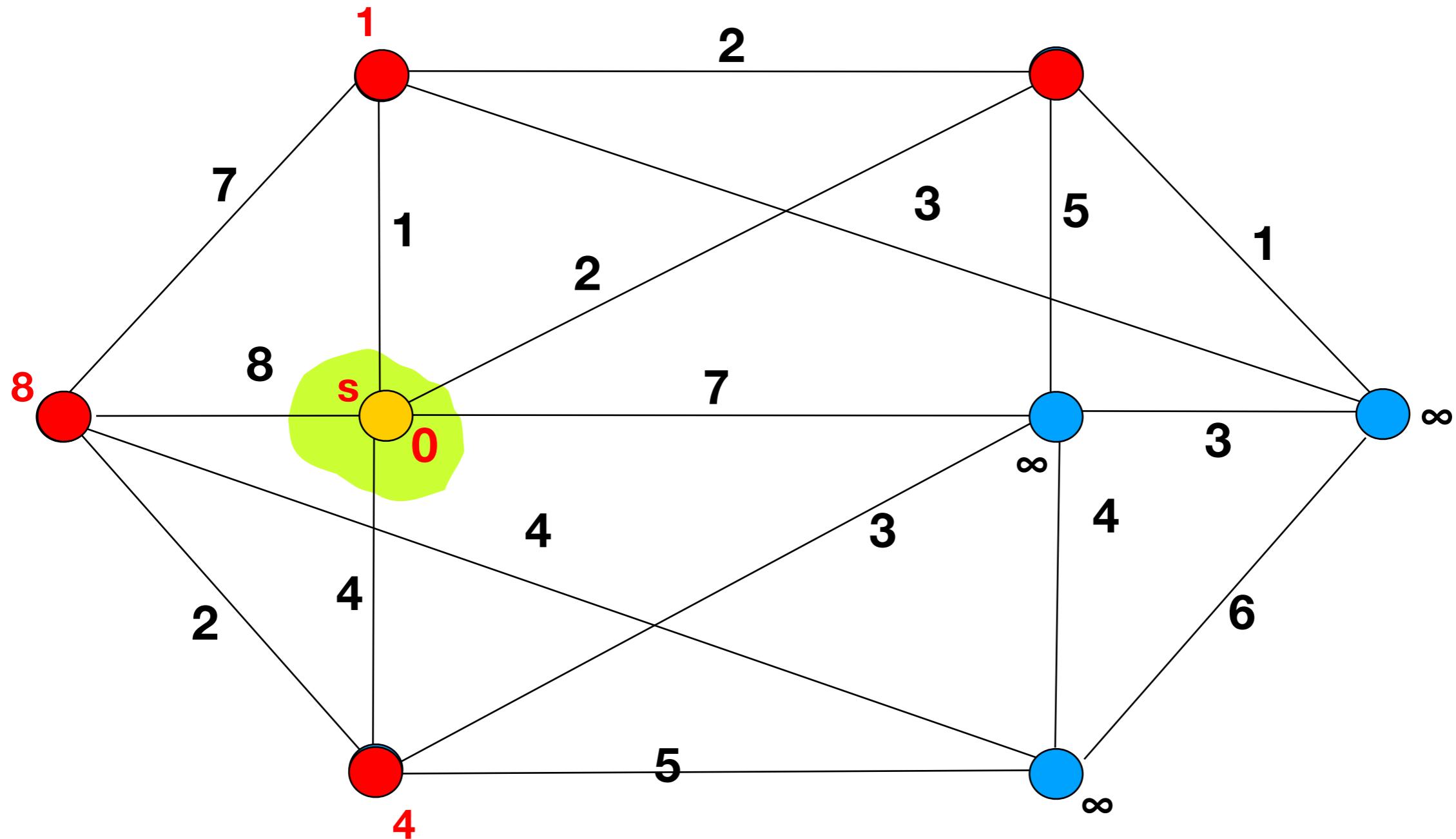
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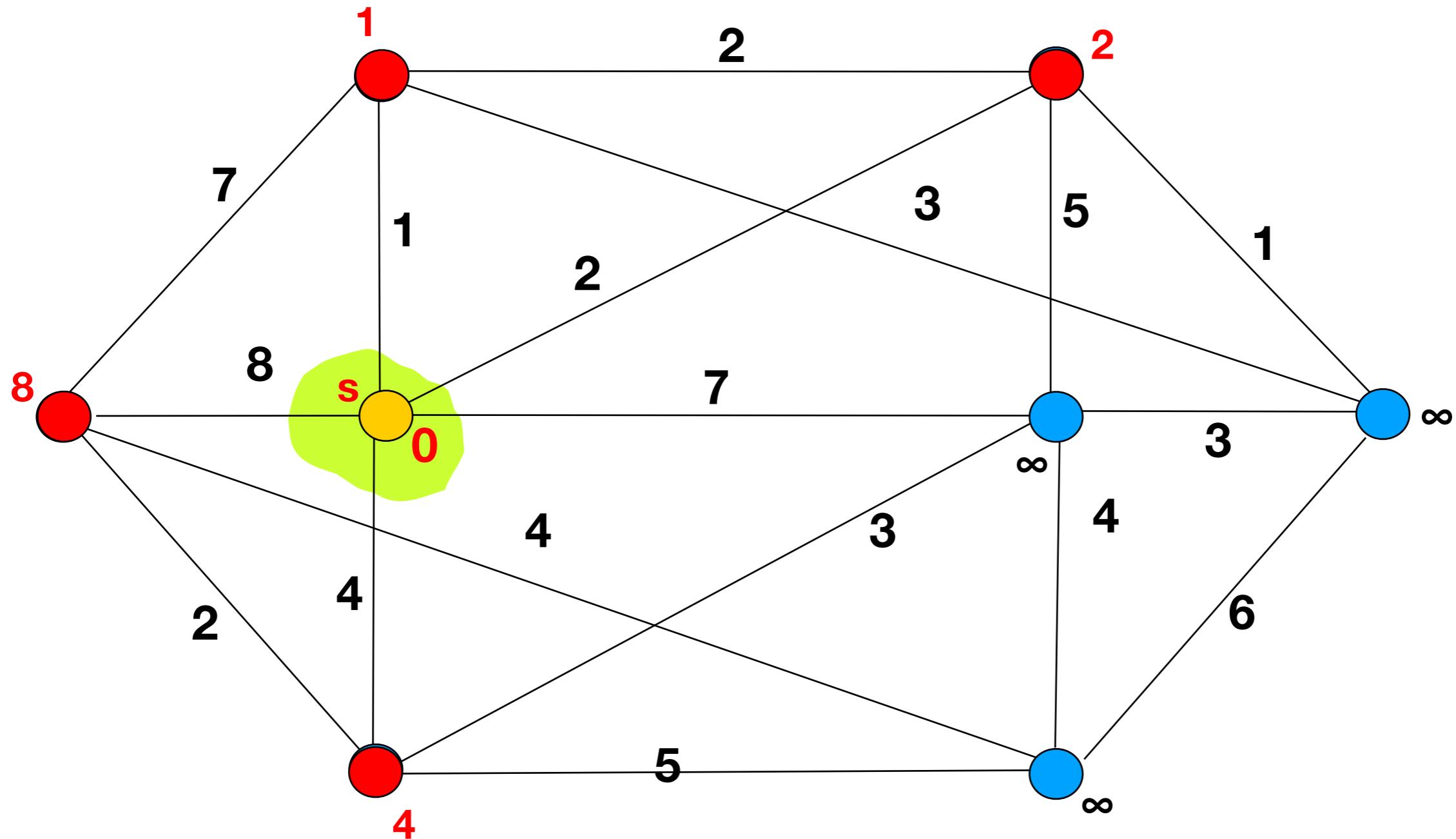
# Dijkstra's Algorithm



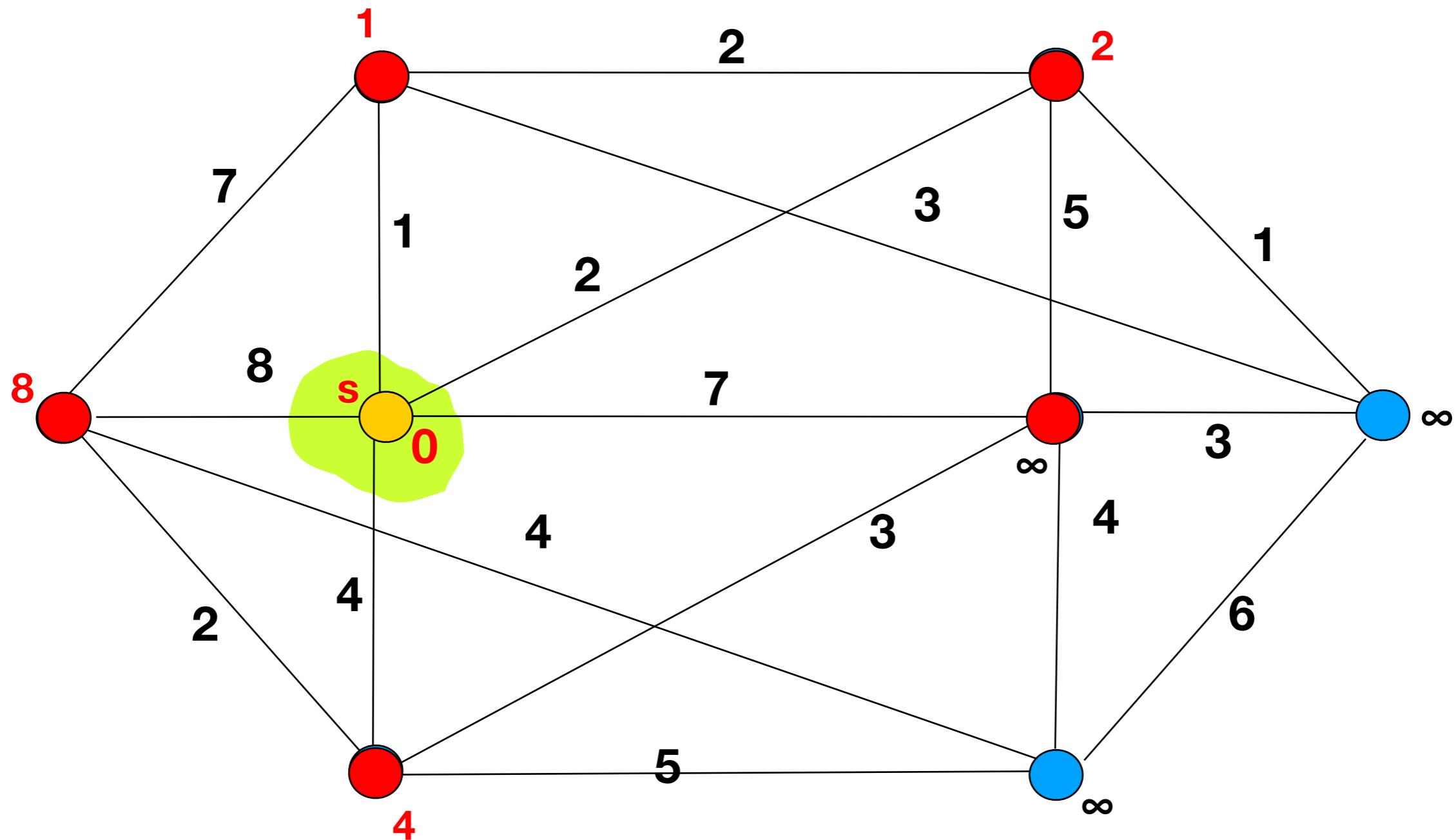
# Dijkstra's Algorithm



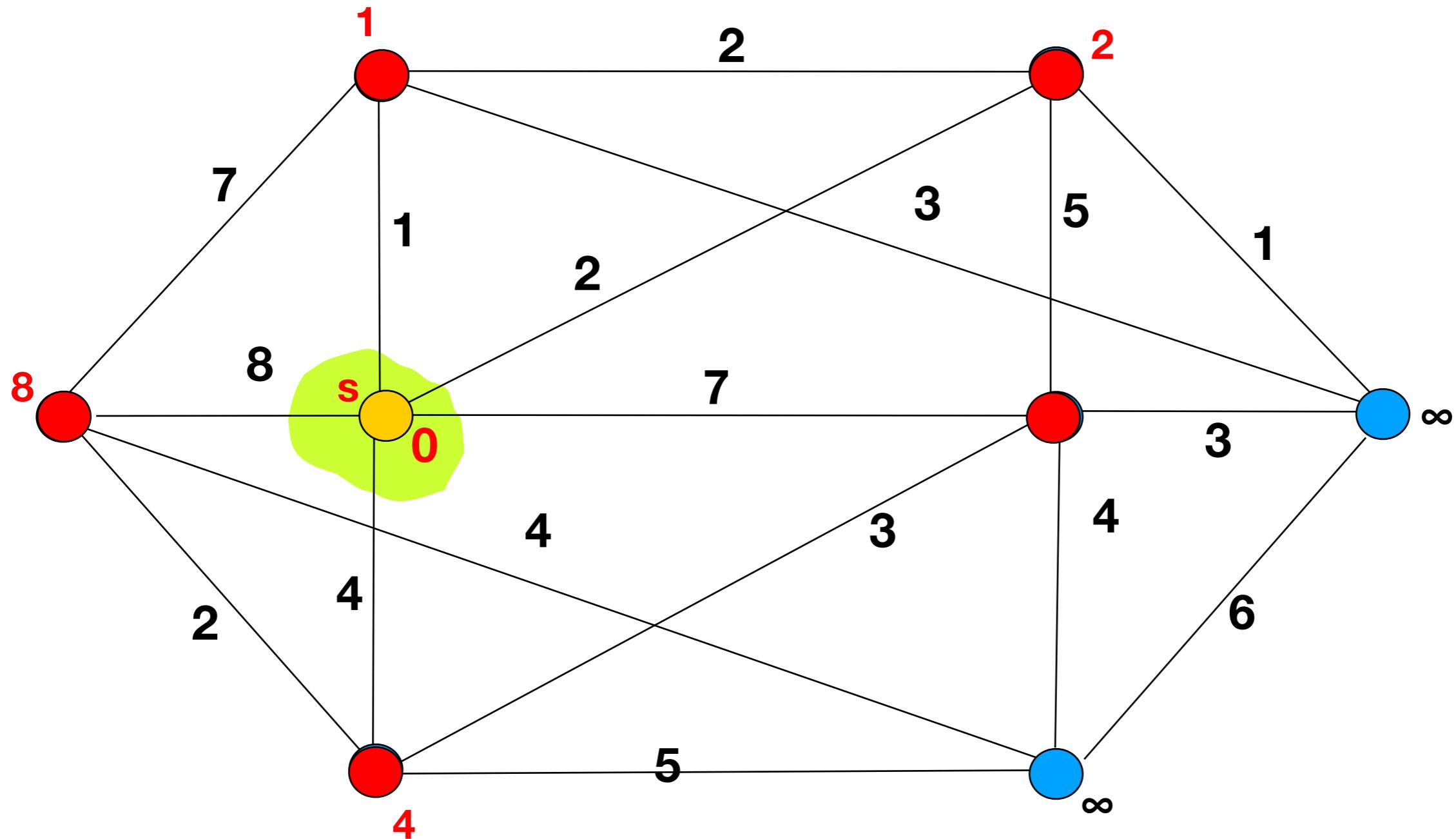
# Dijkstra's Algorithm



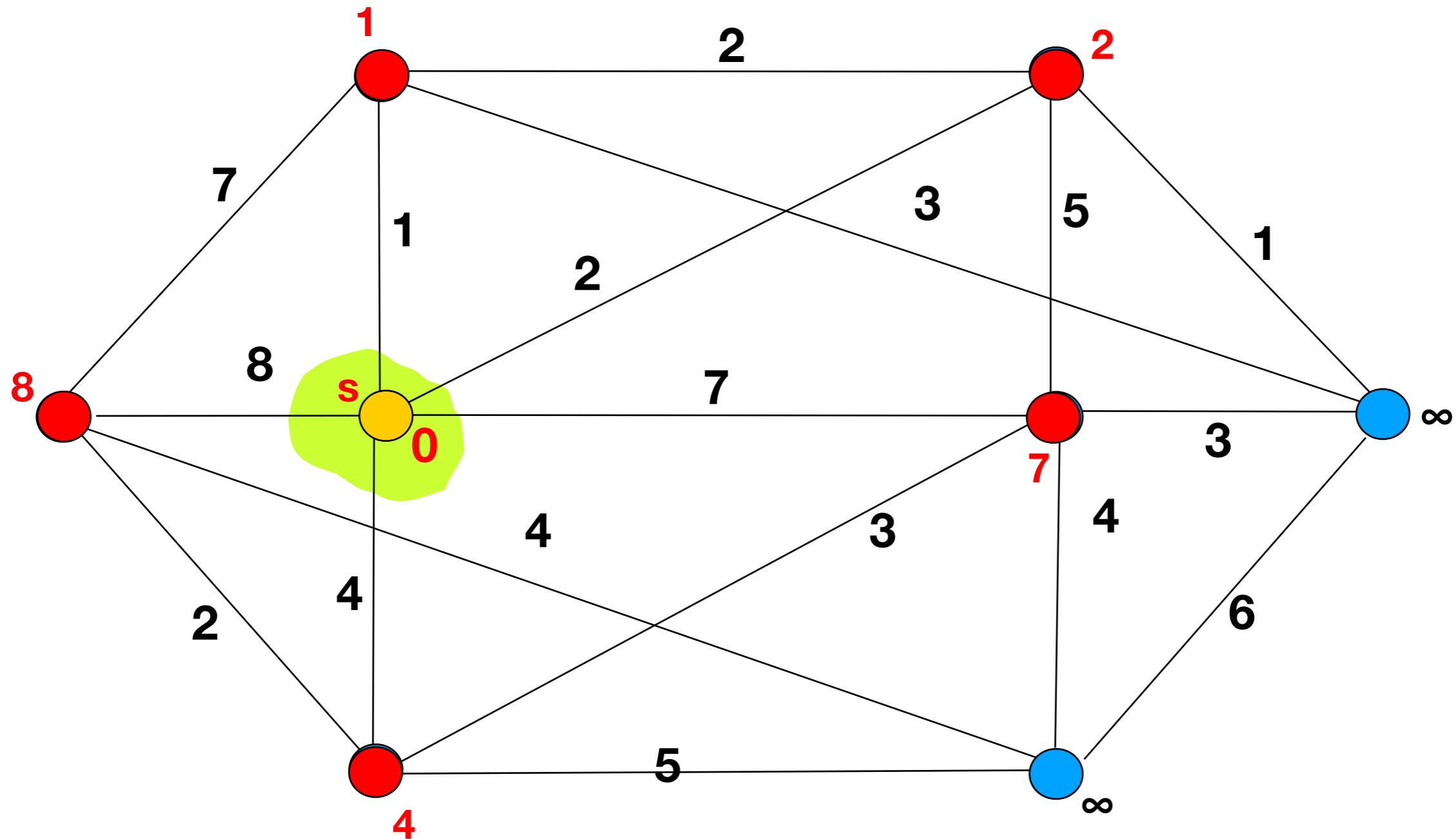
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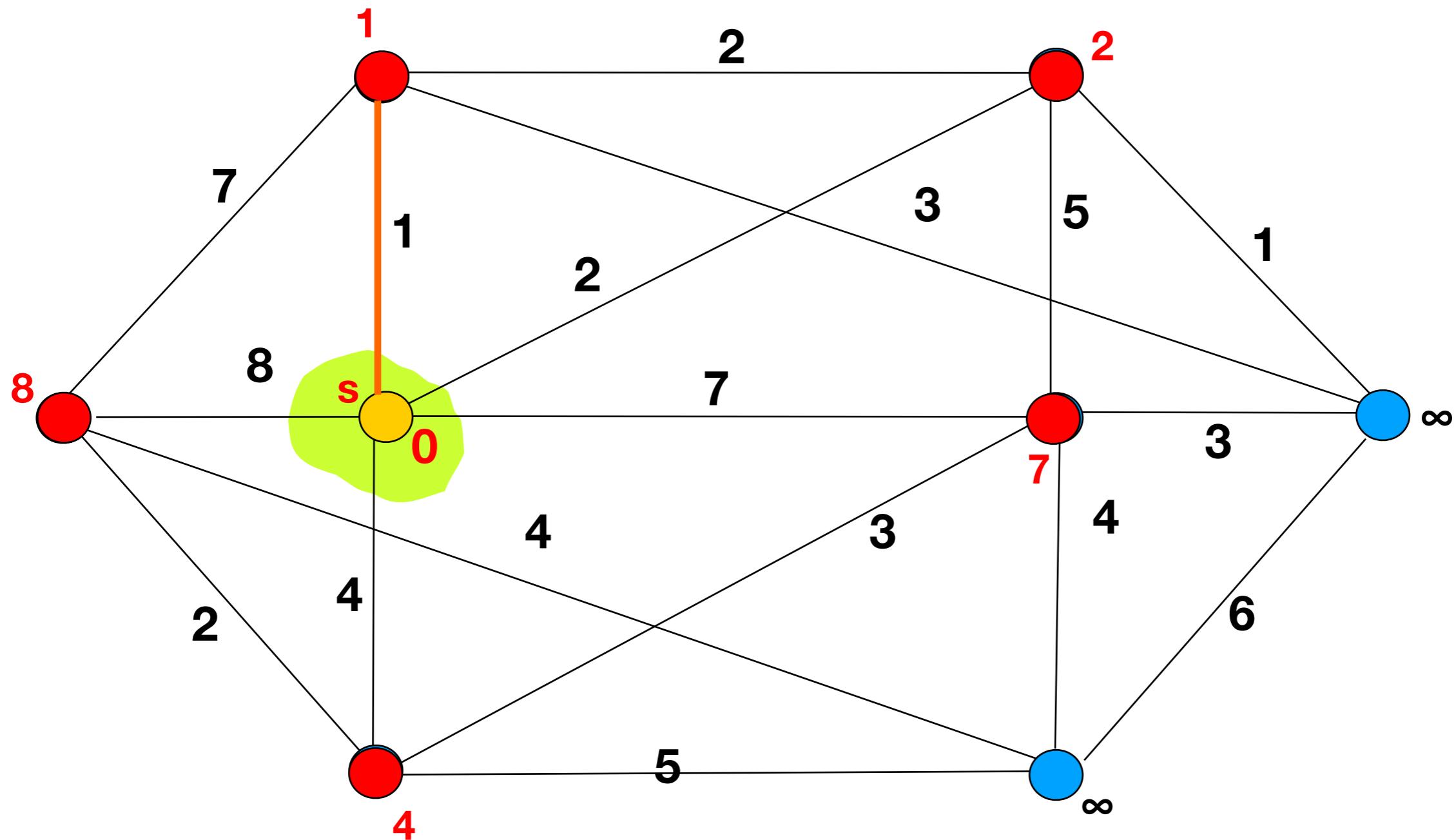
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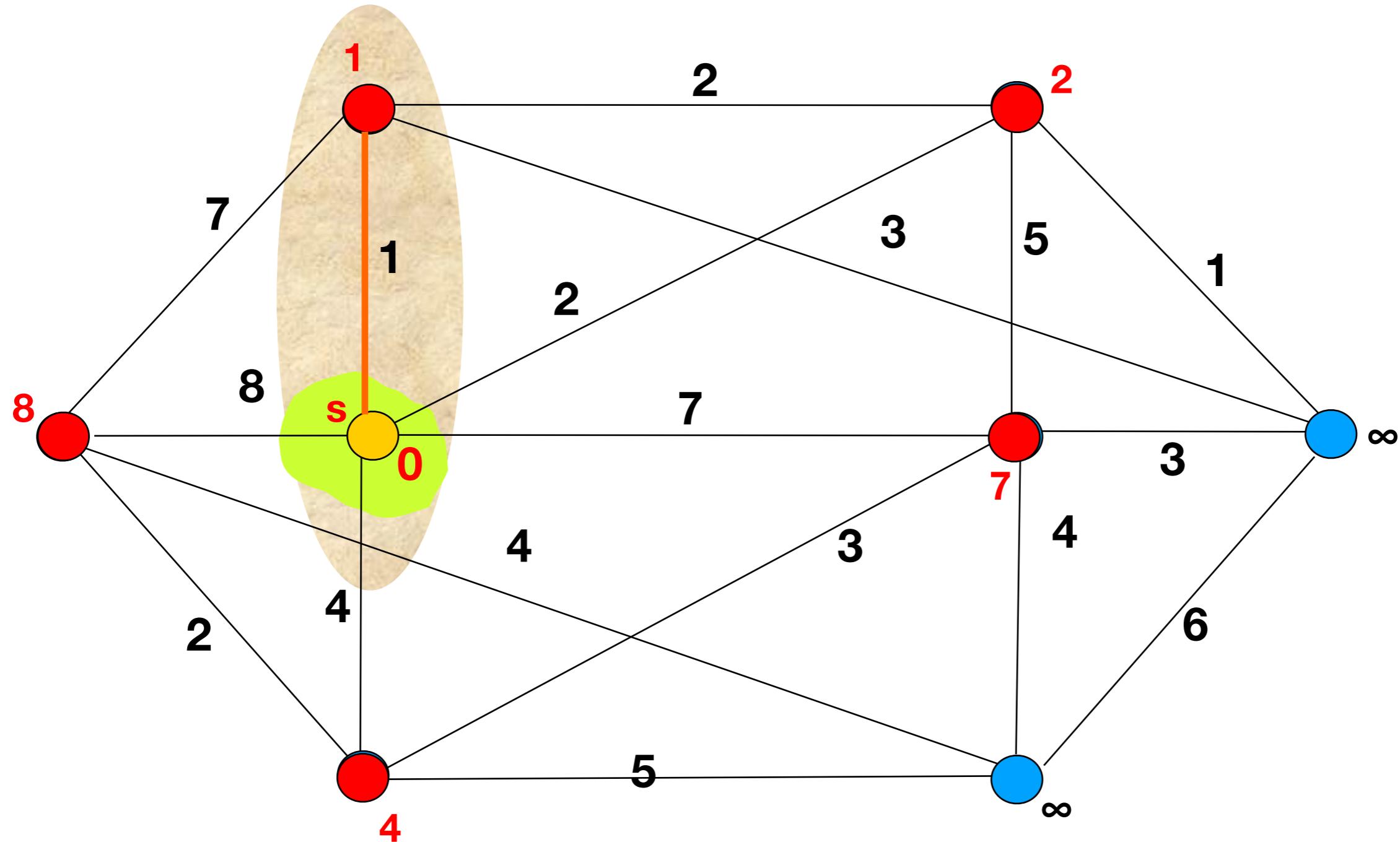
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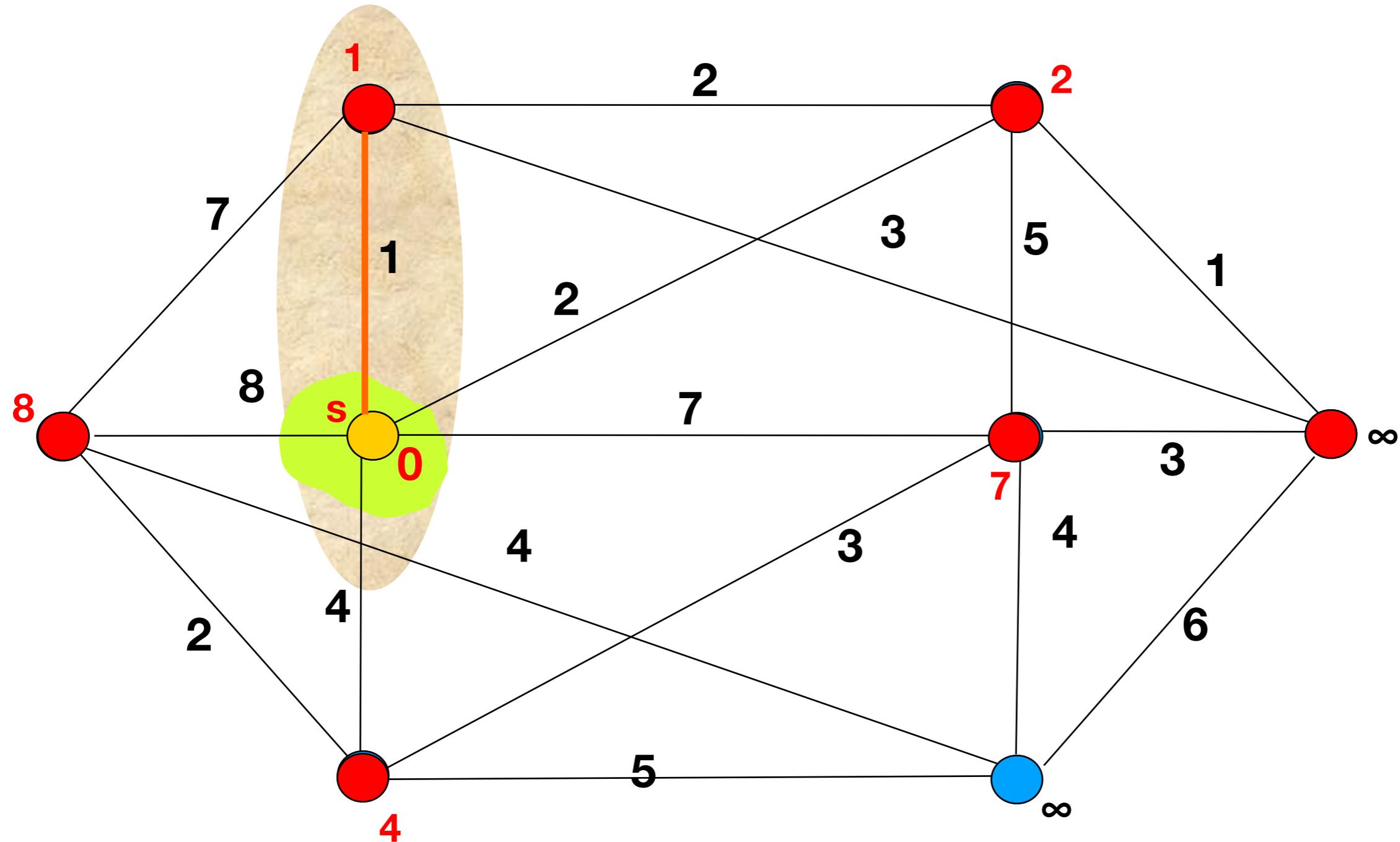
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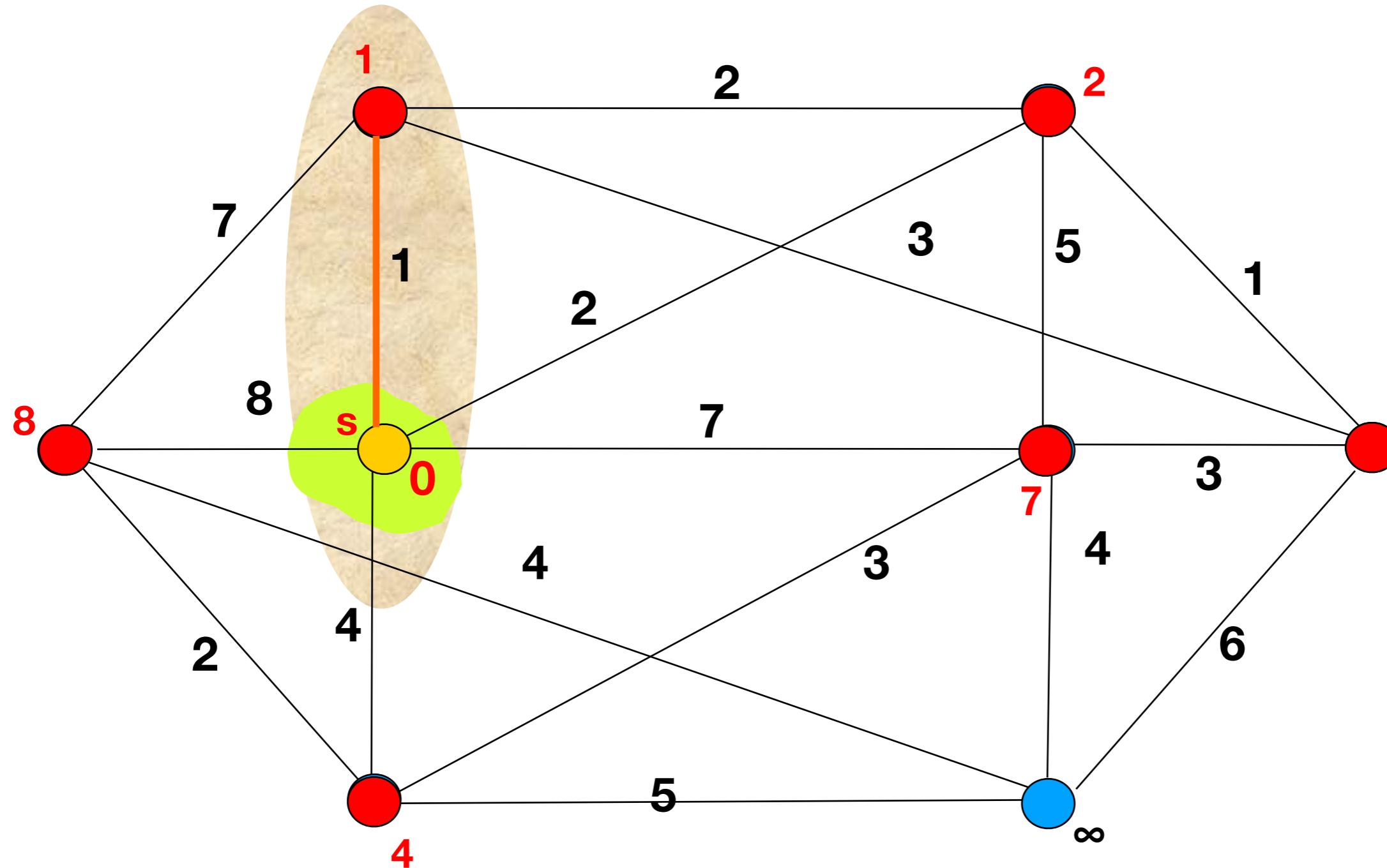
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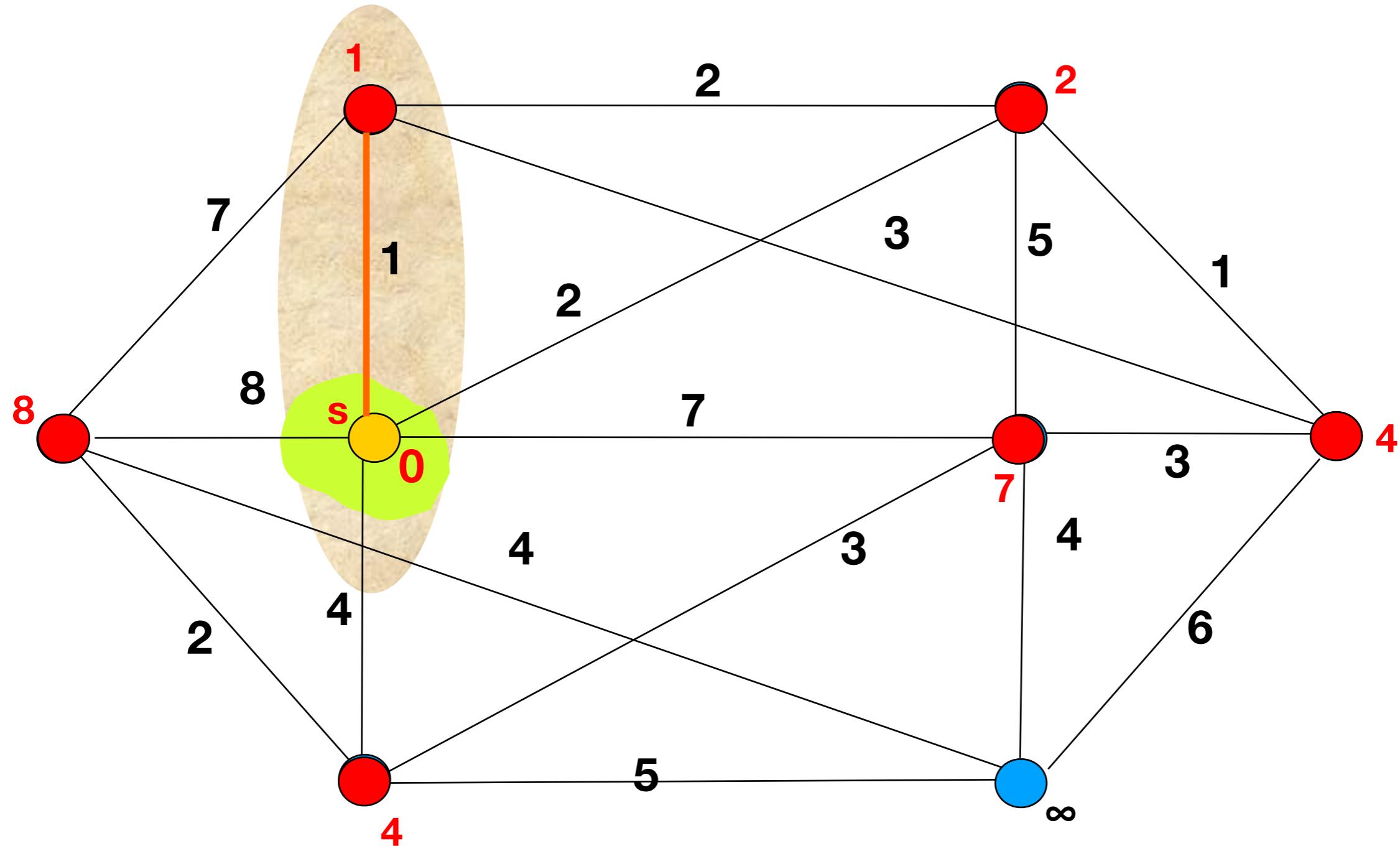
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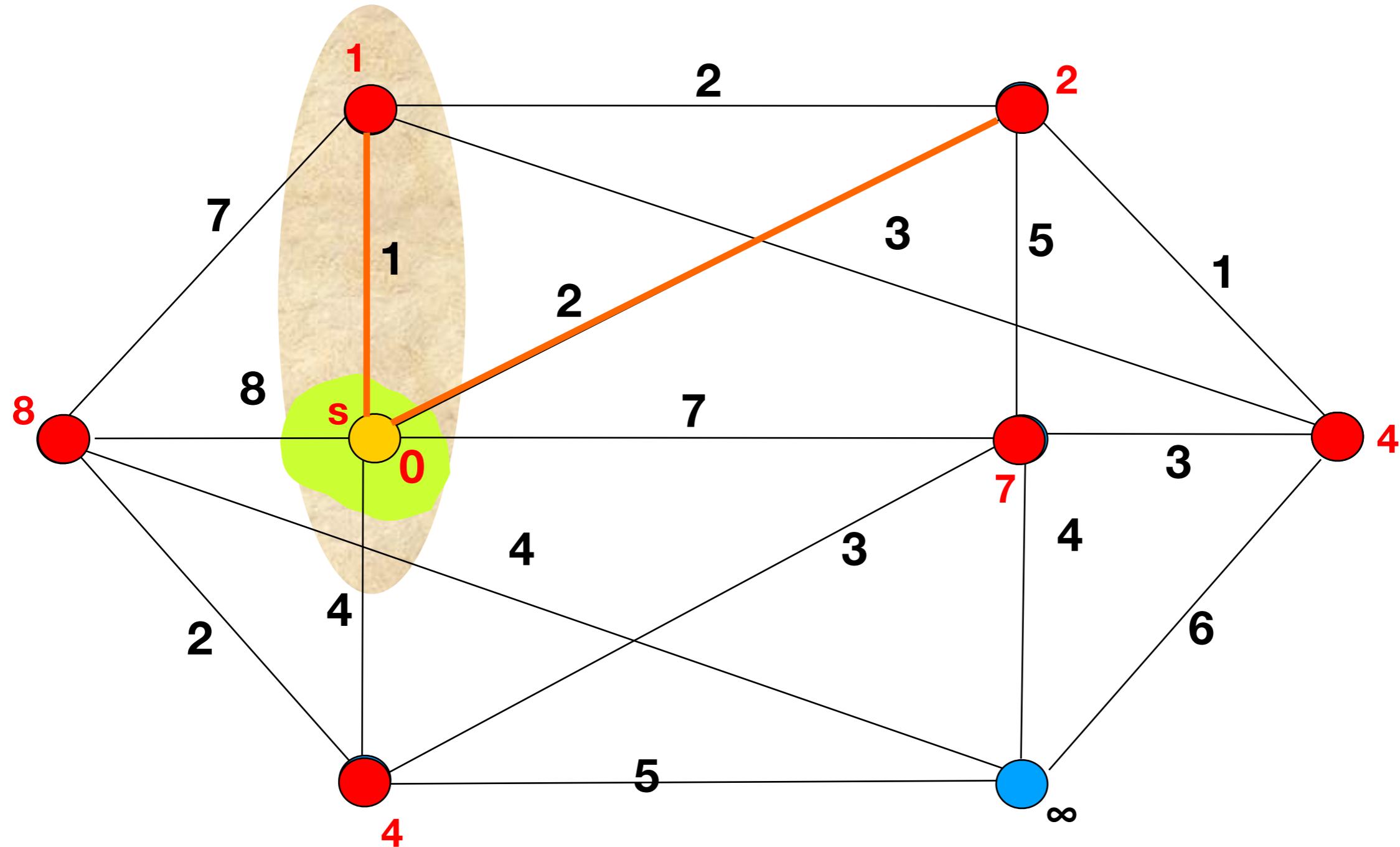
# Dijkstra's Algorithm



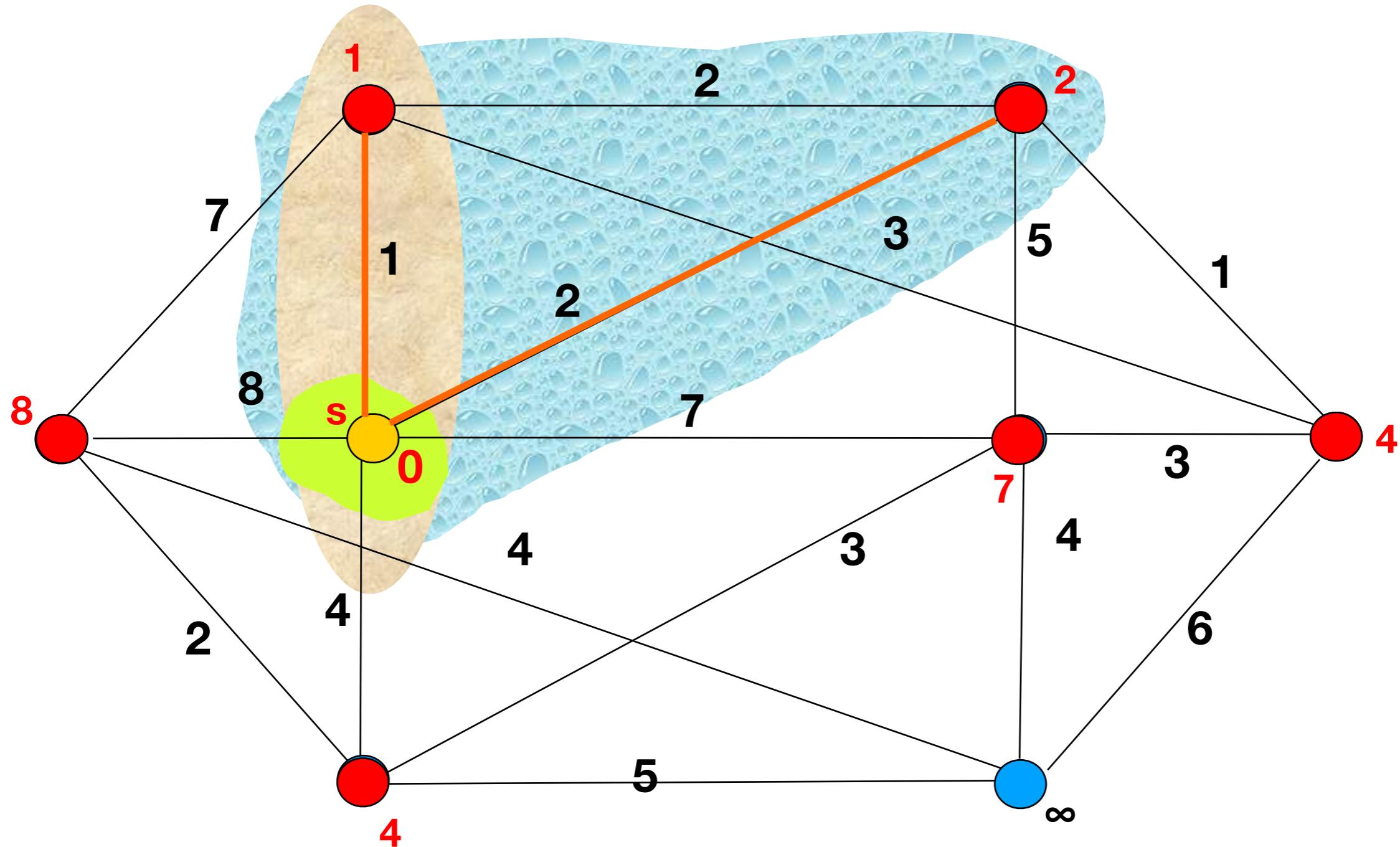
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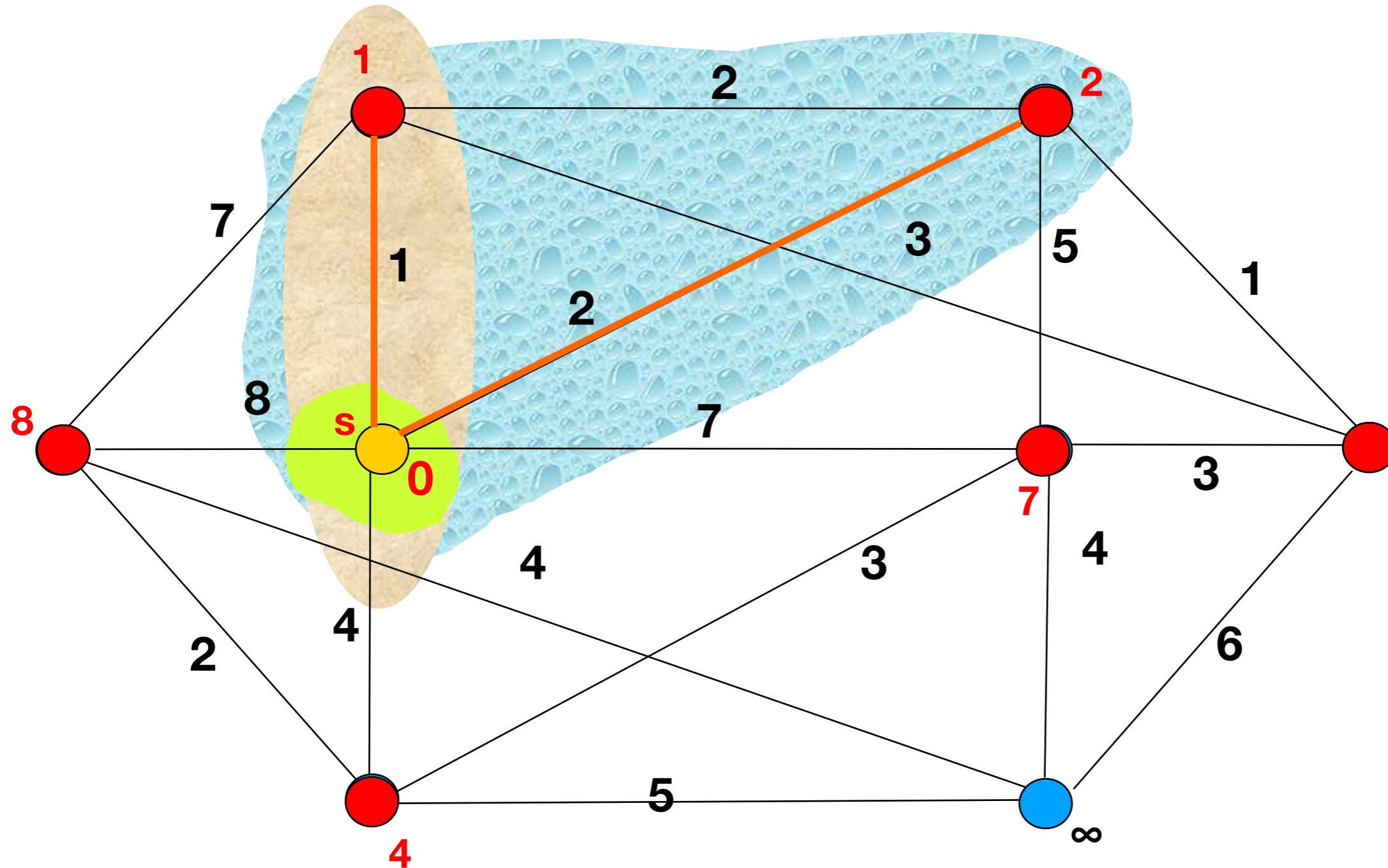
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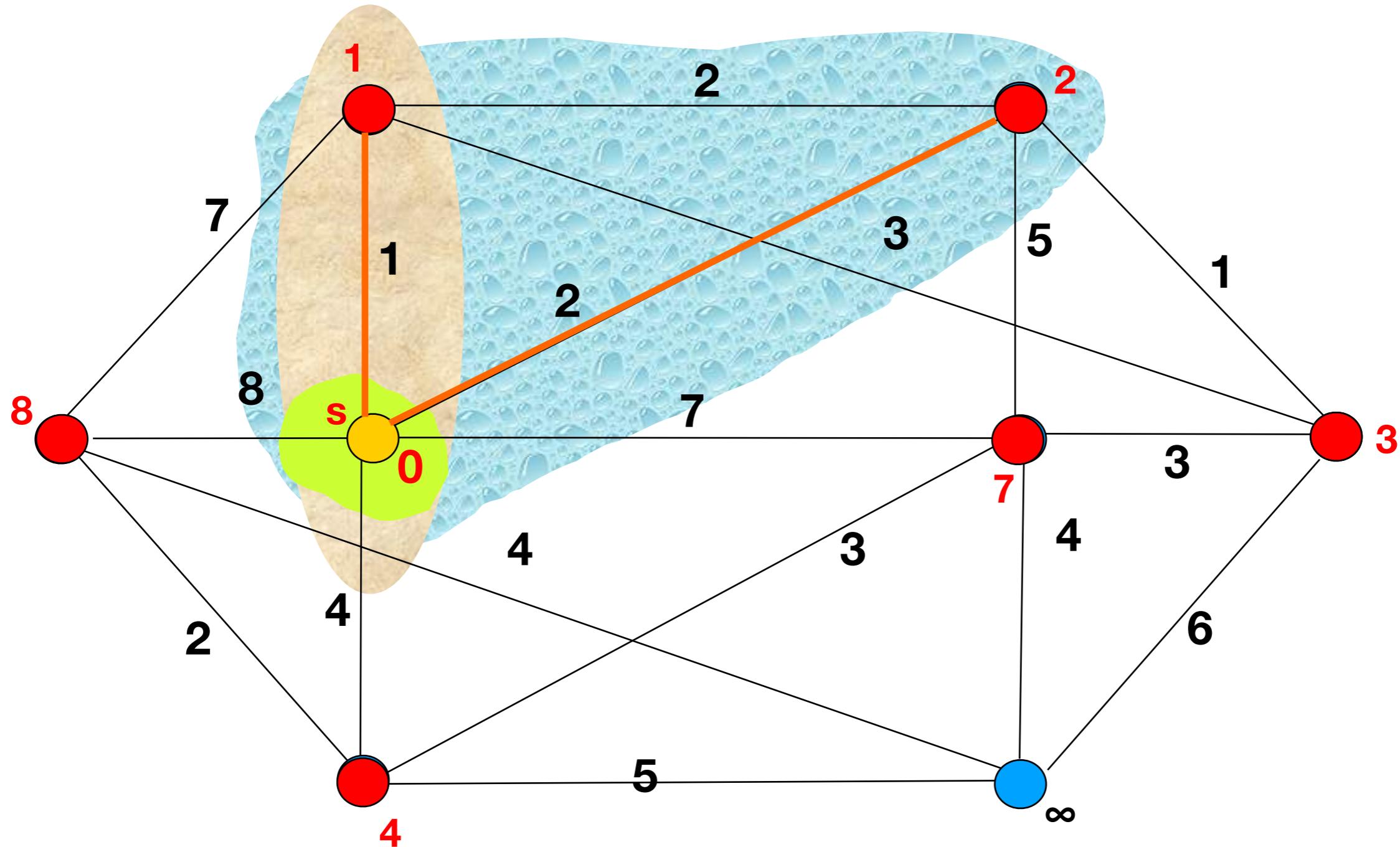
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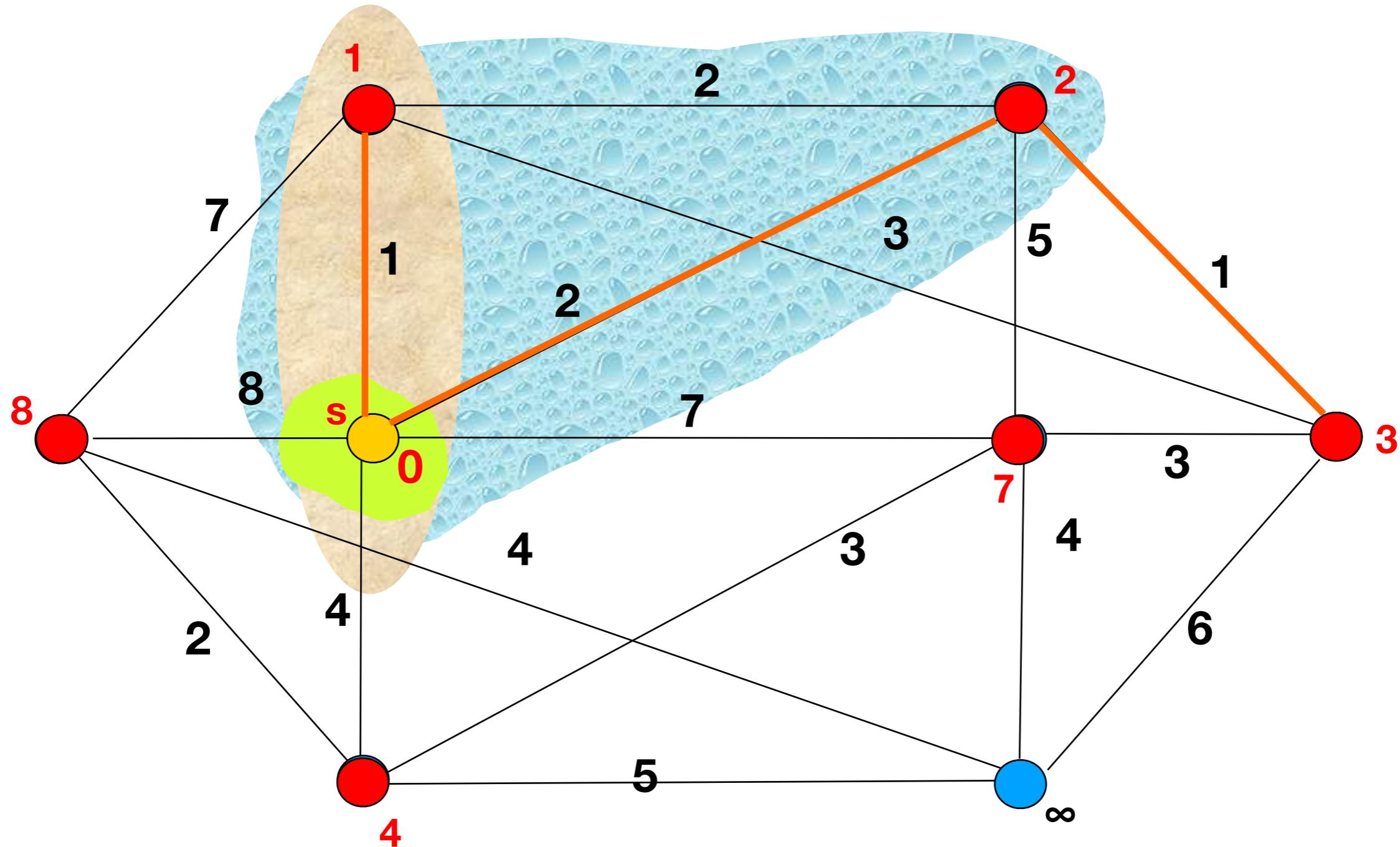
# Dijkstra's Algorithm



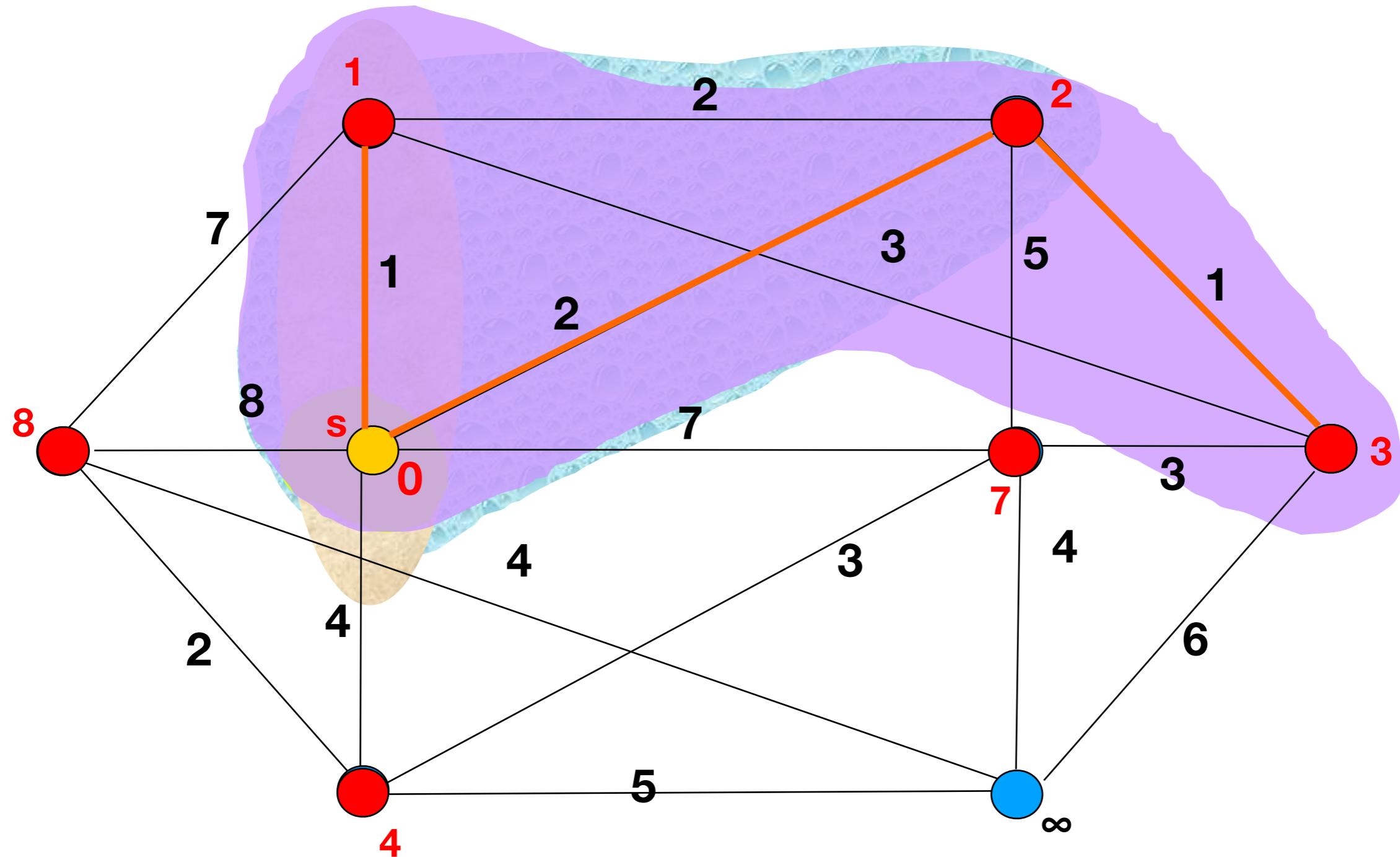
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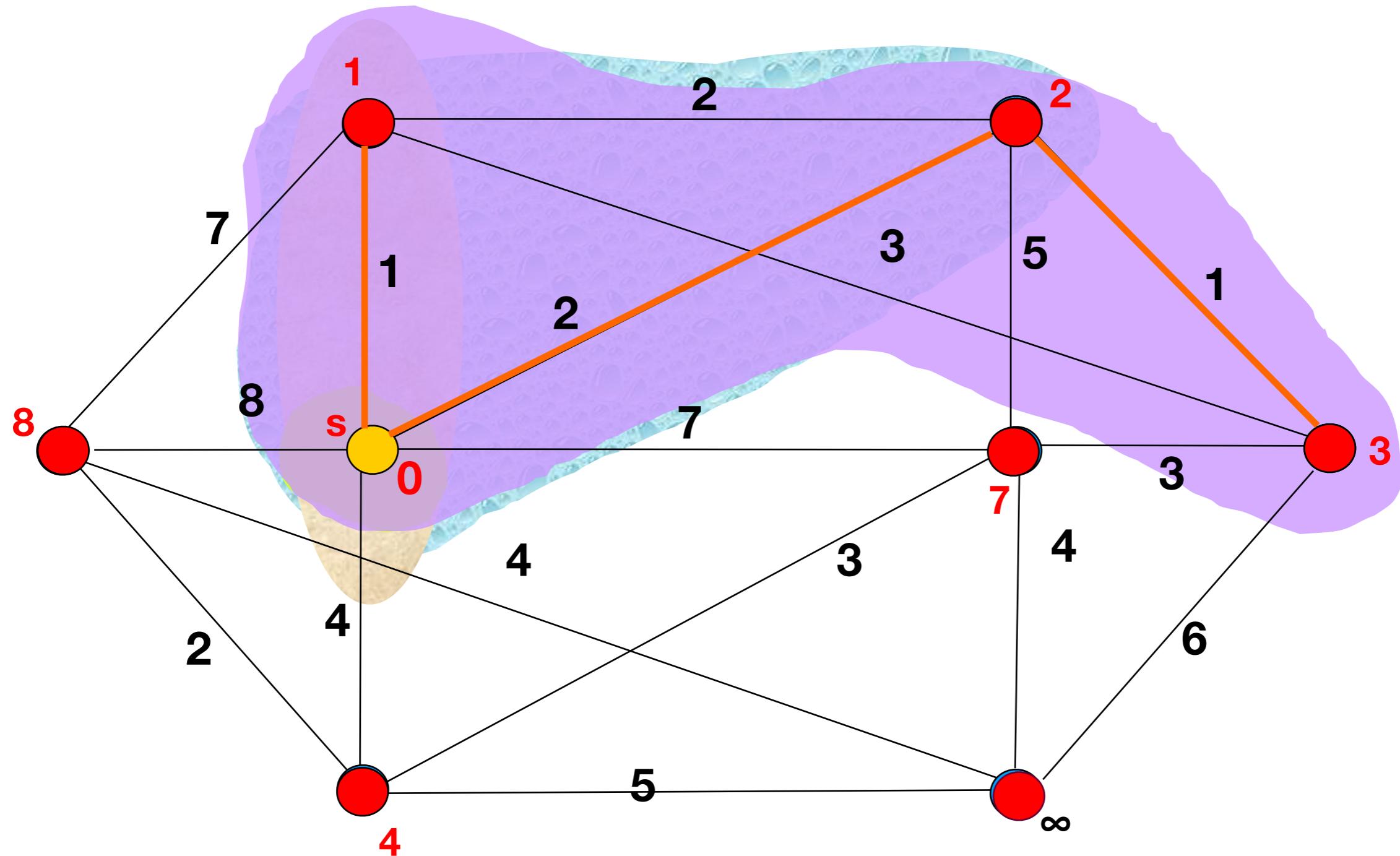
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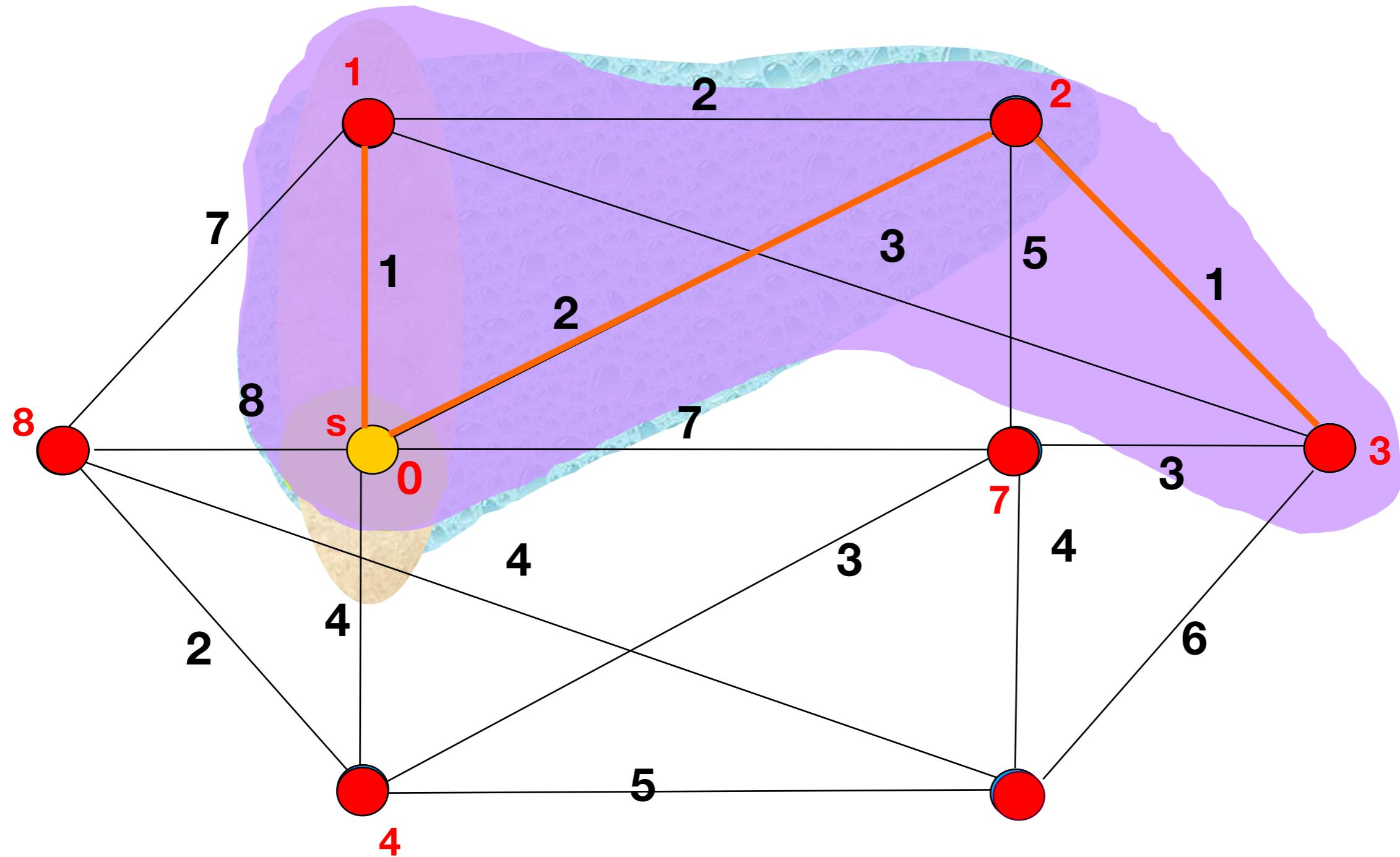
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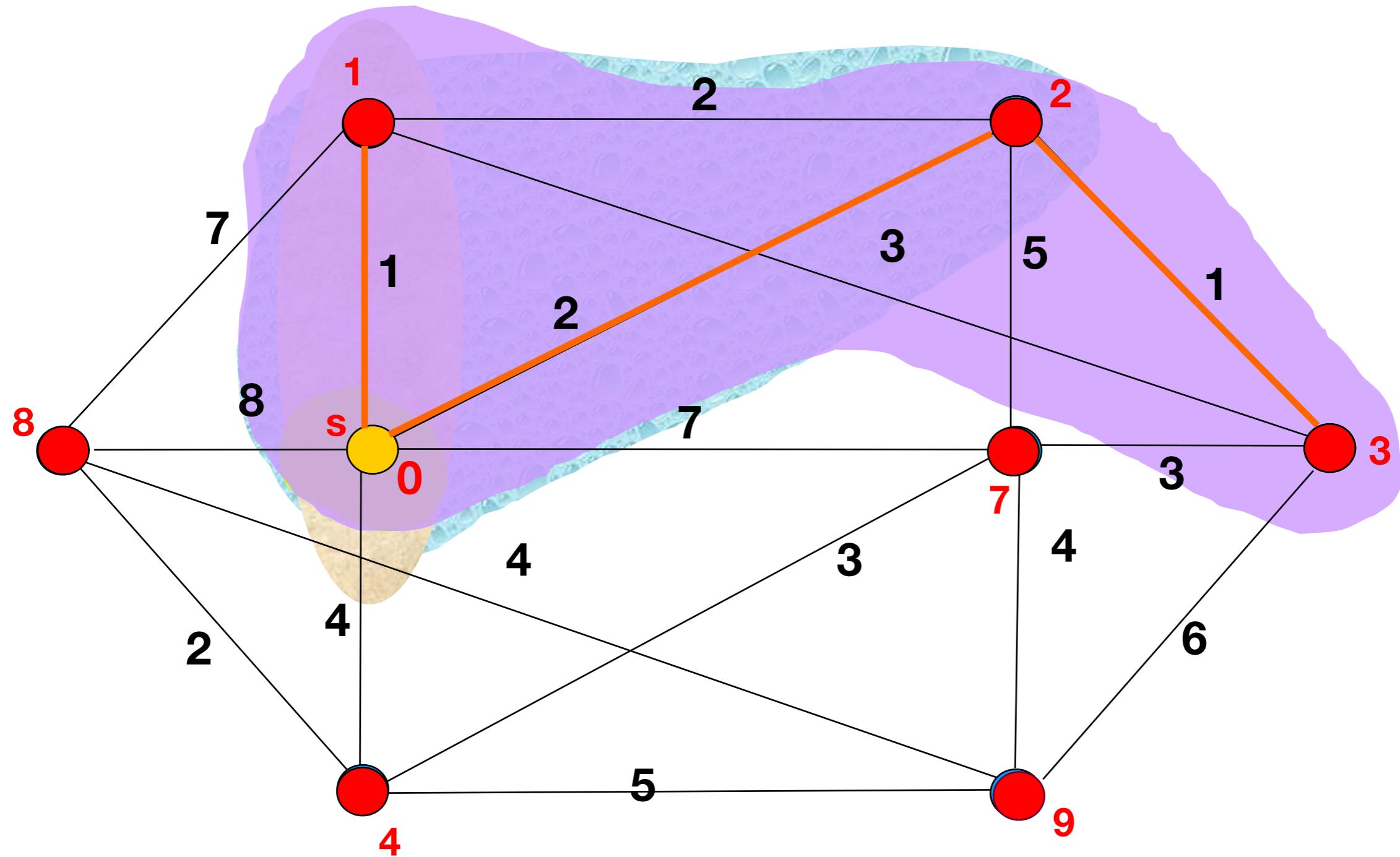
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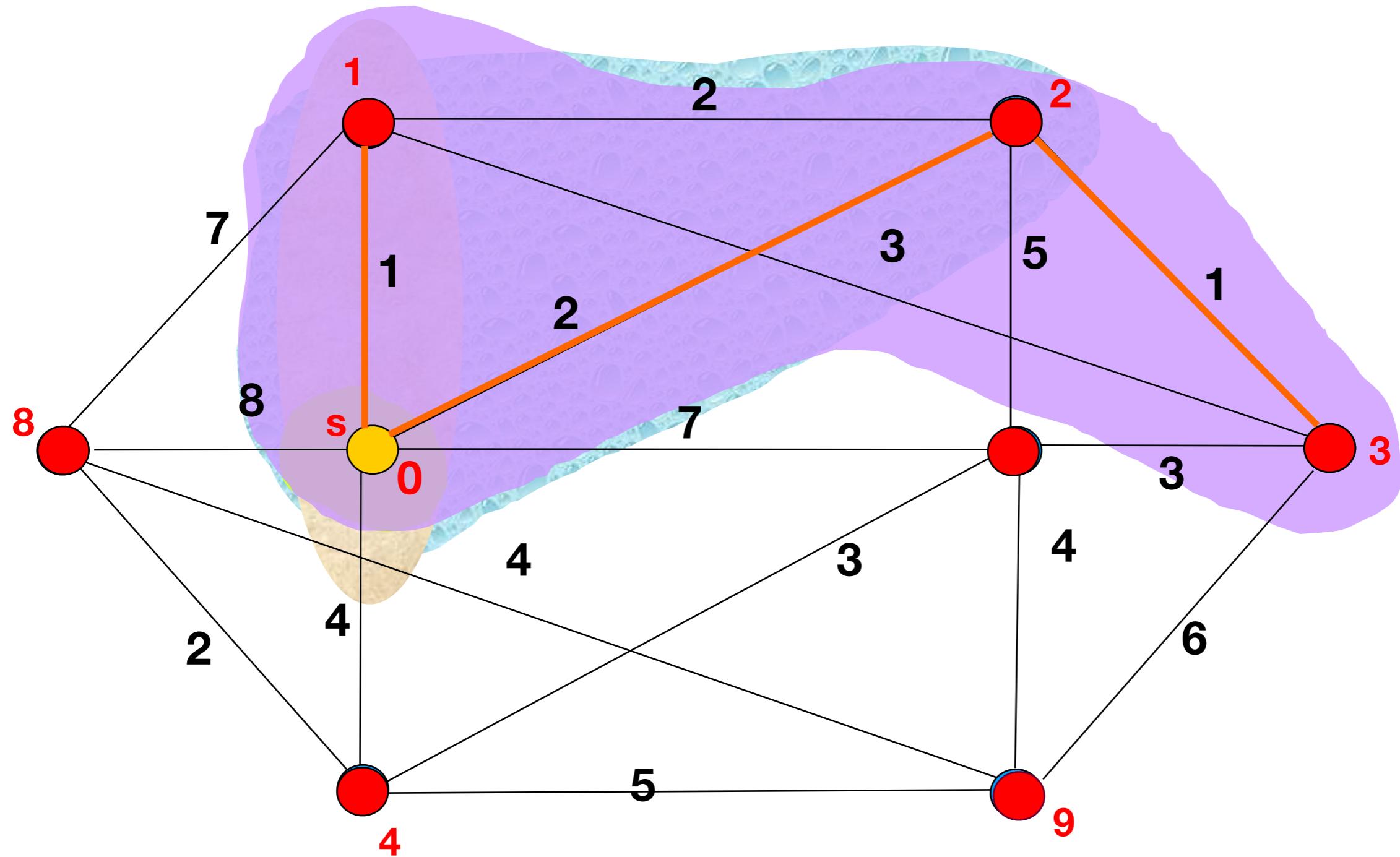
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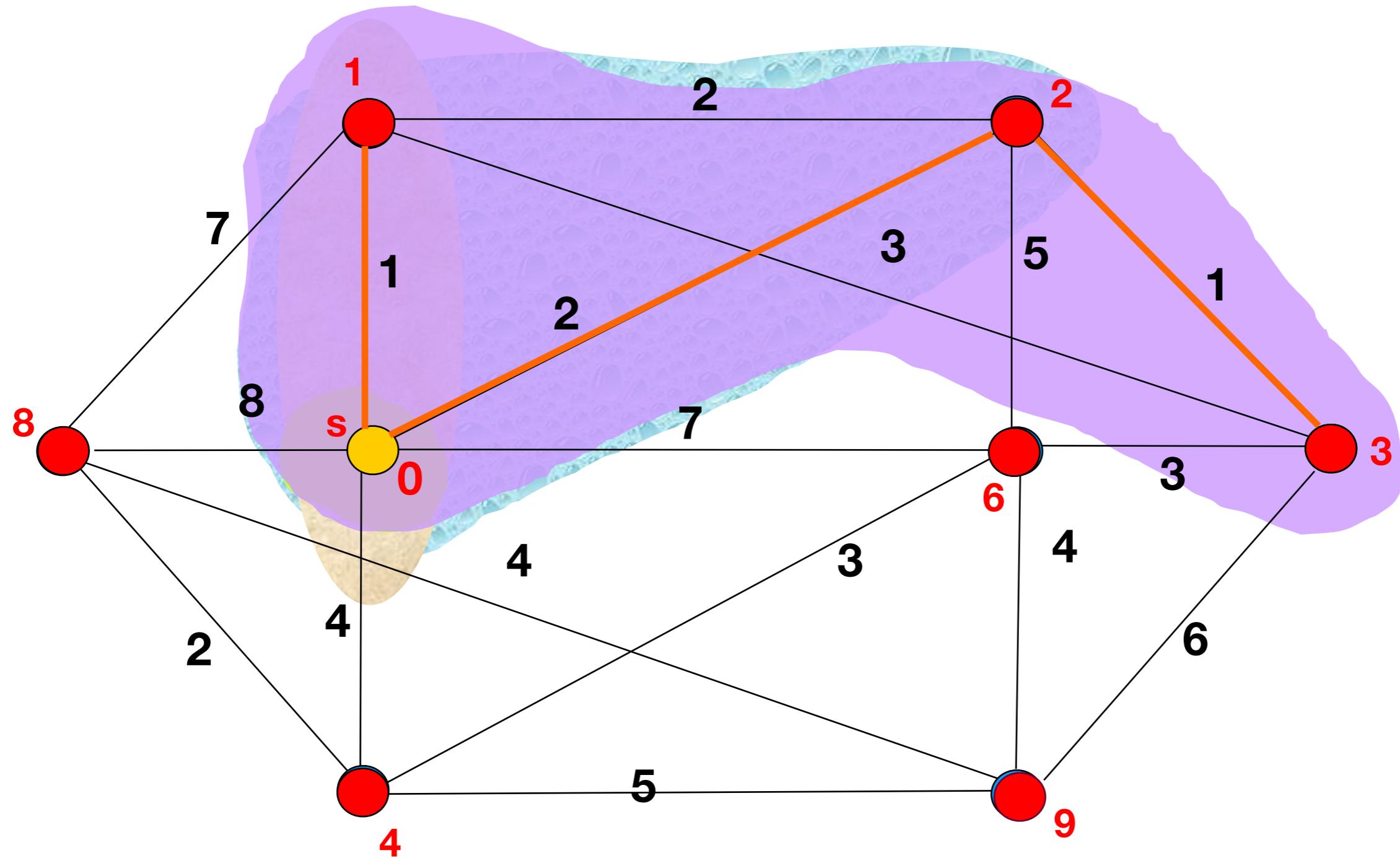
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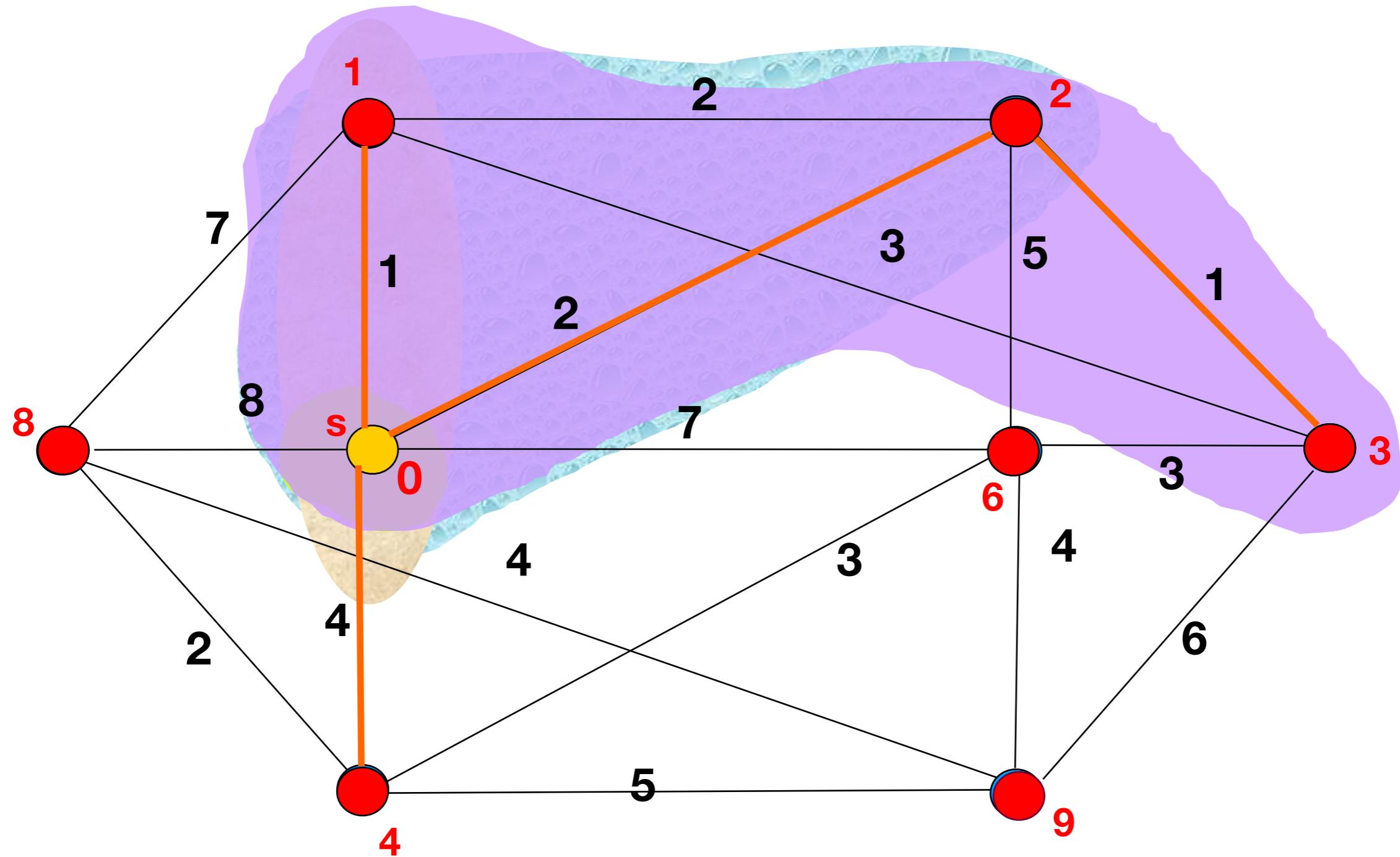
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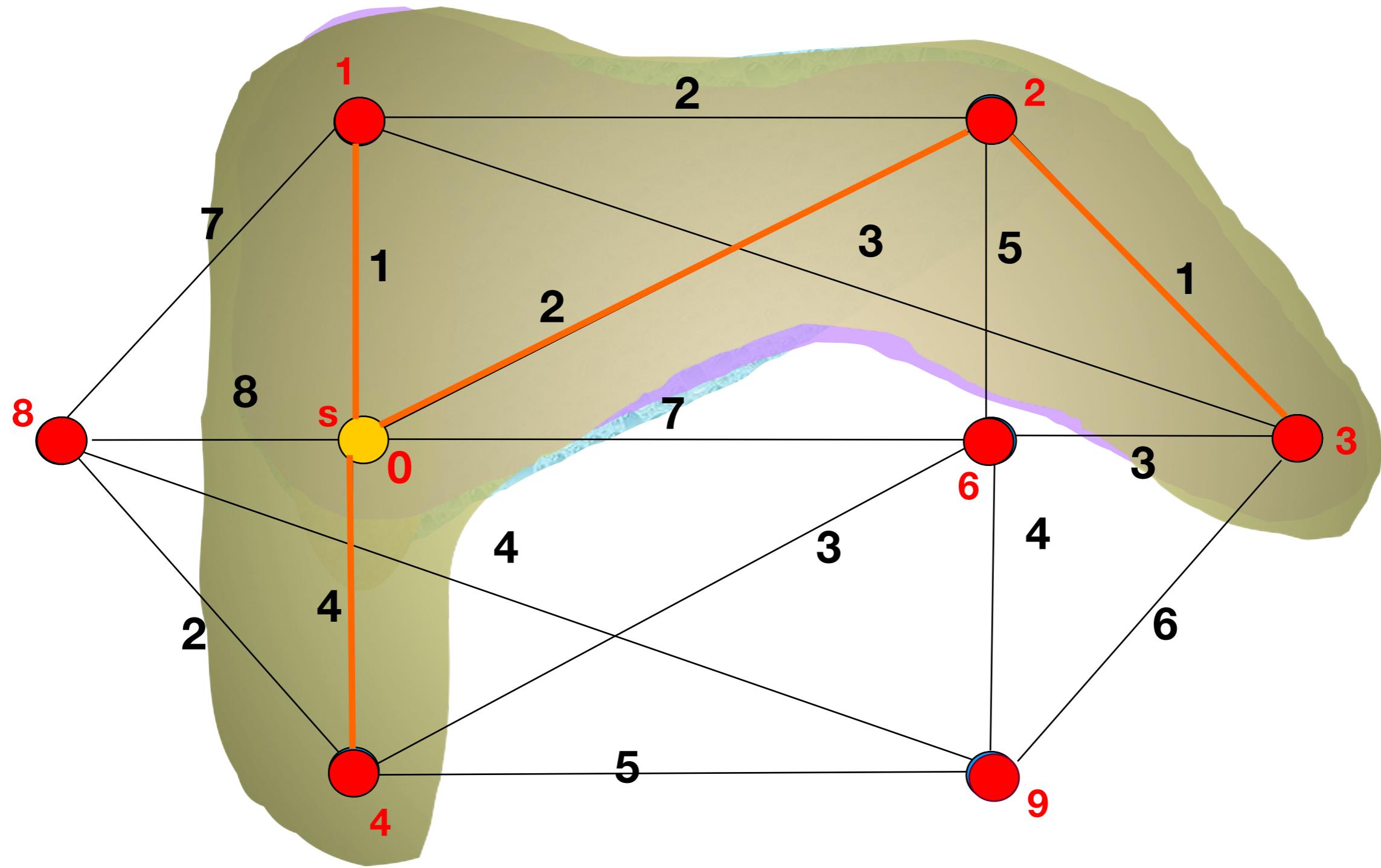
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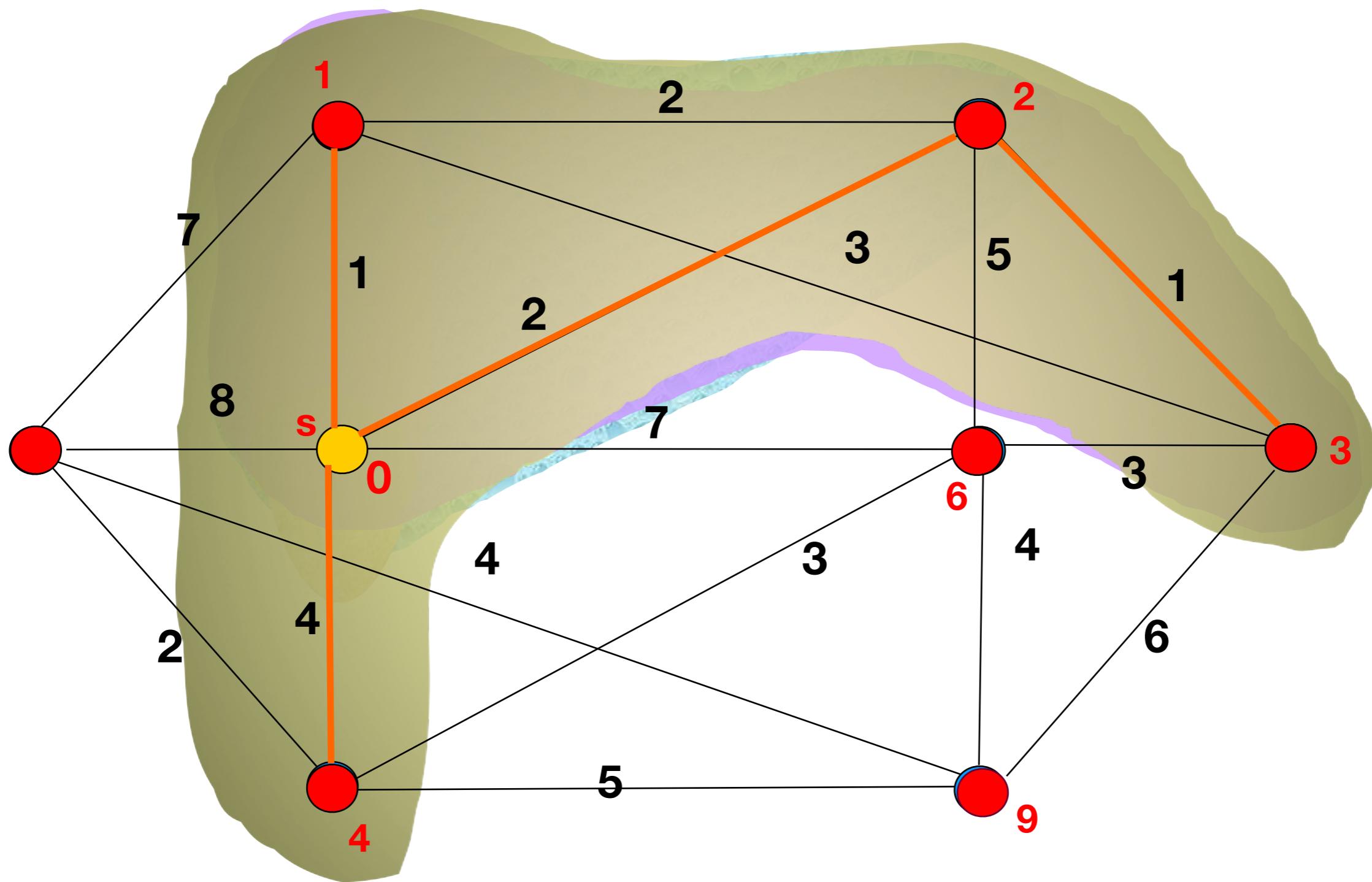
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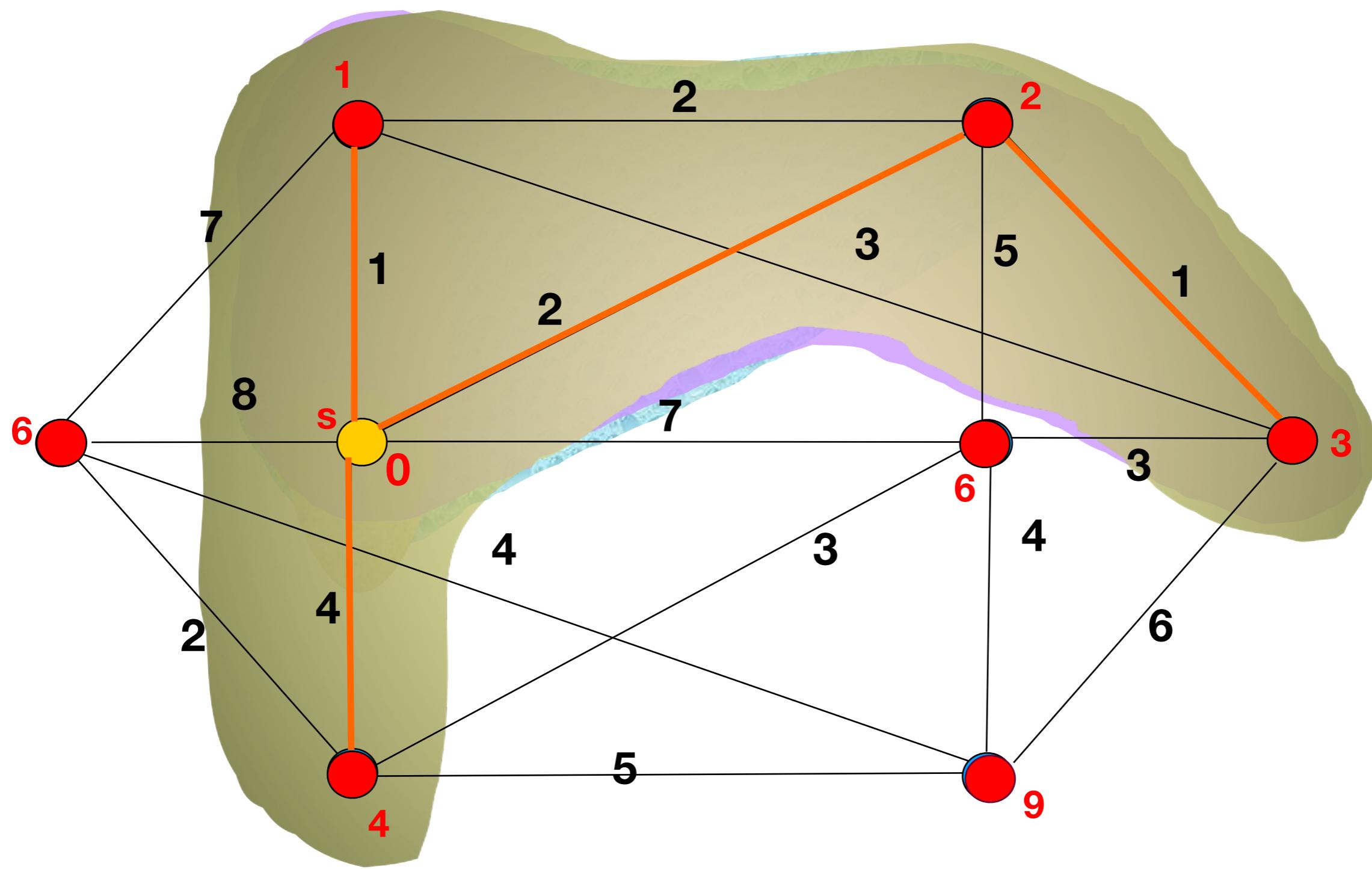
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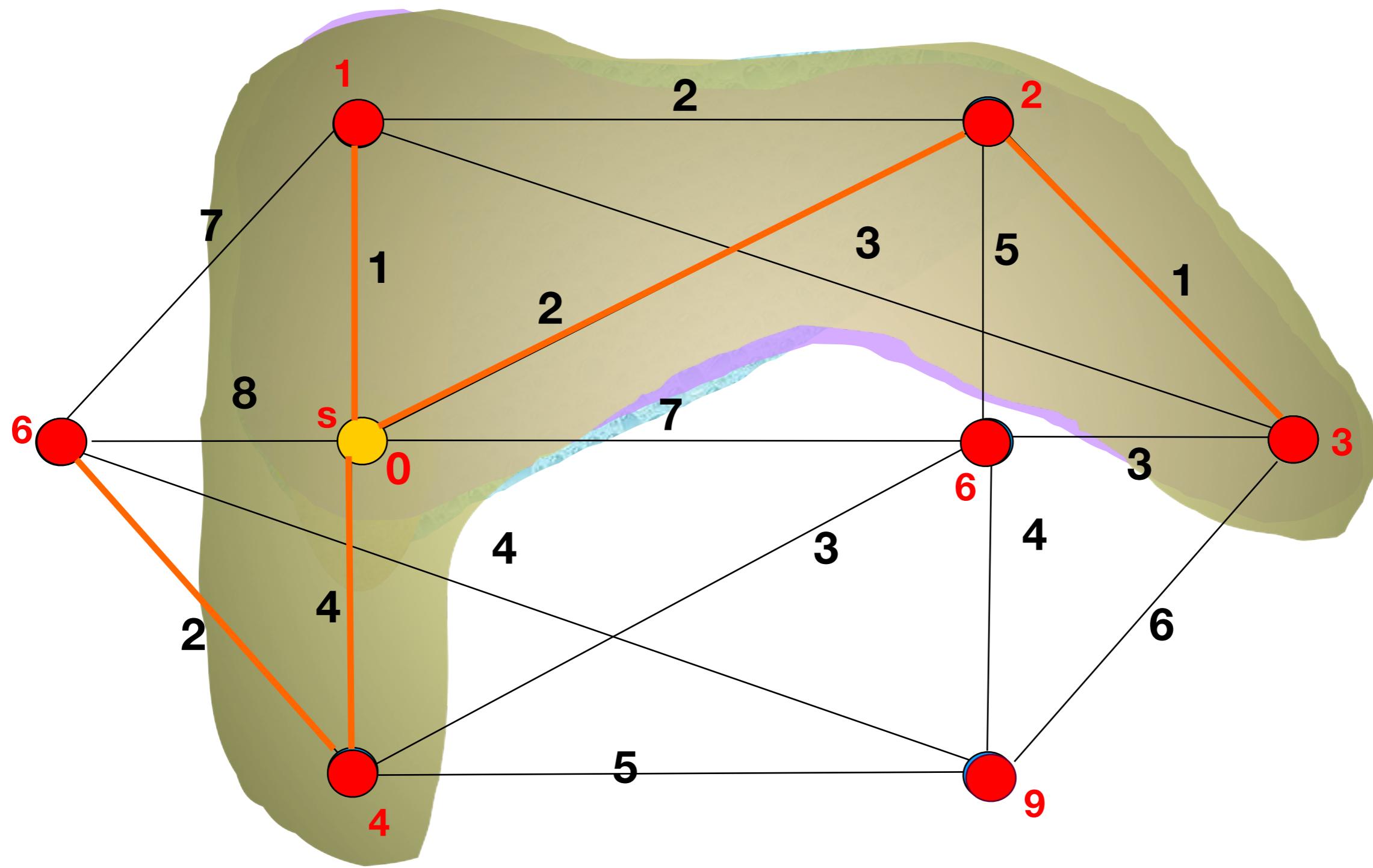
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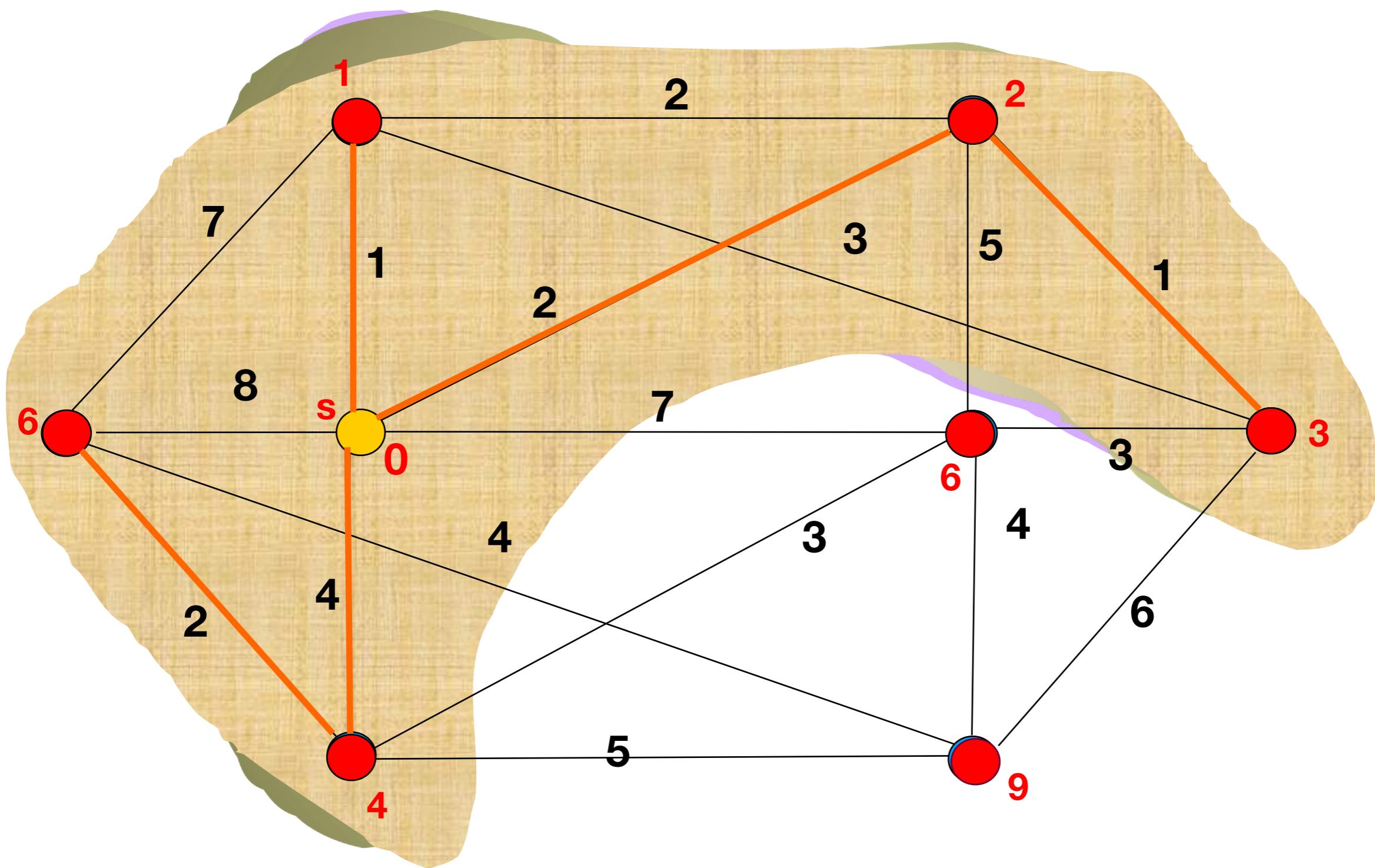
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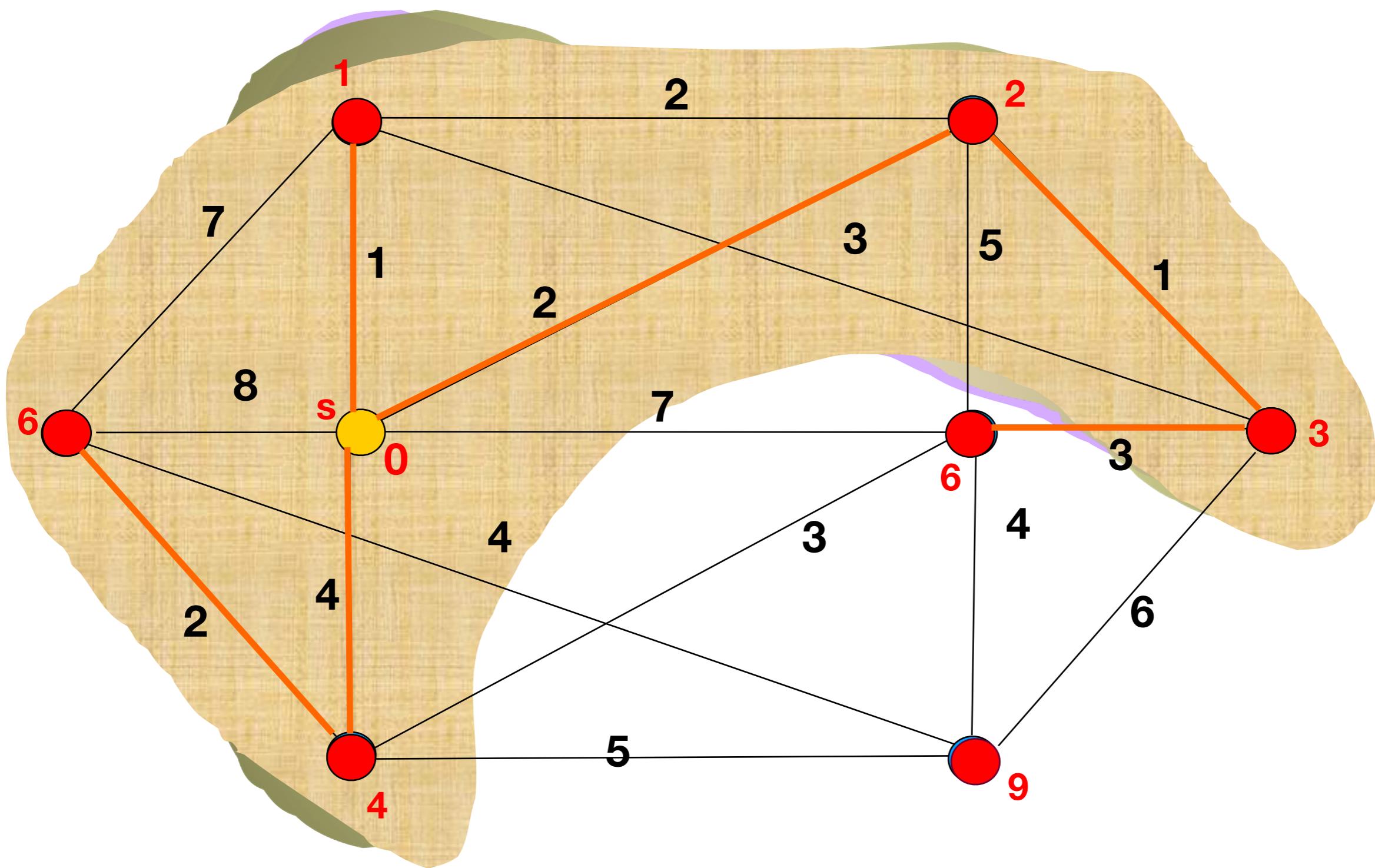
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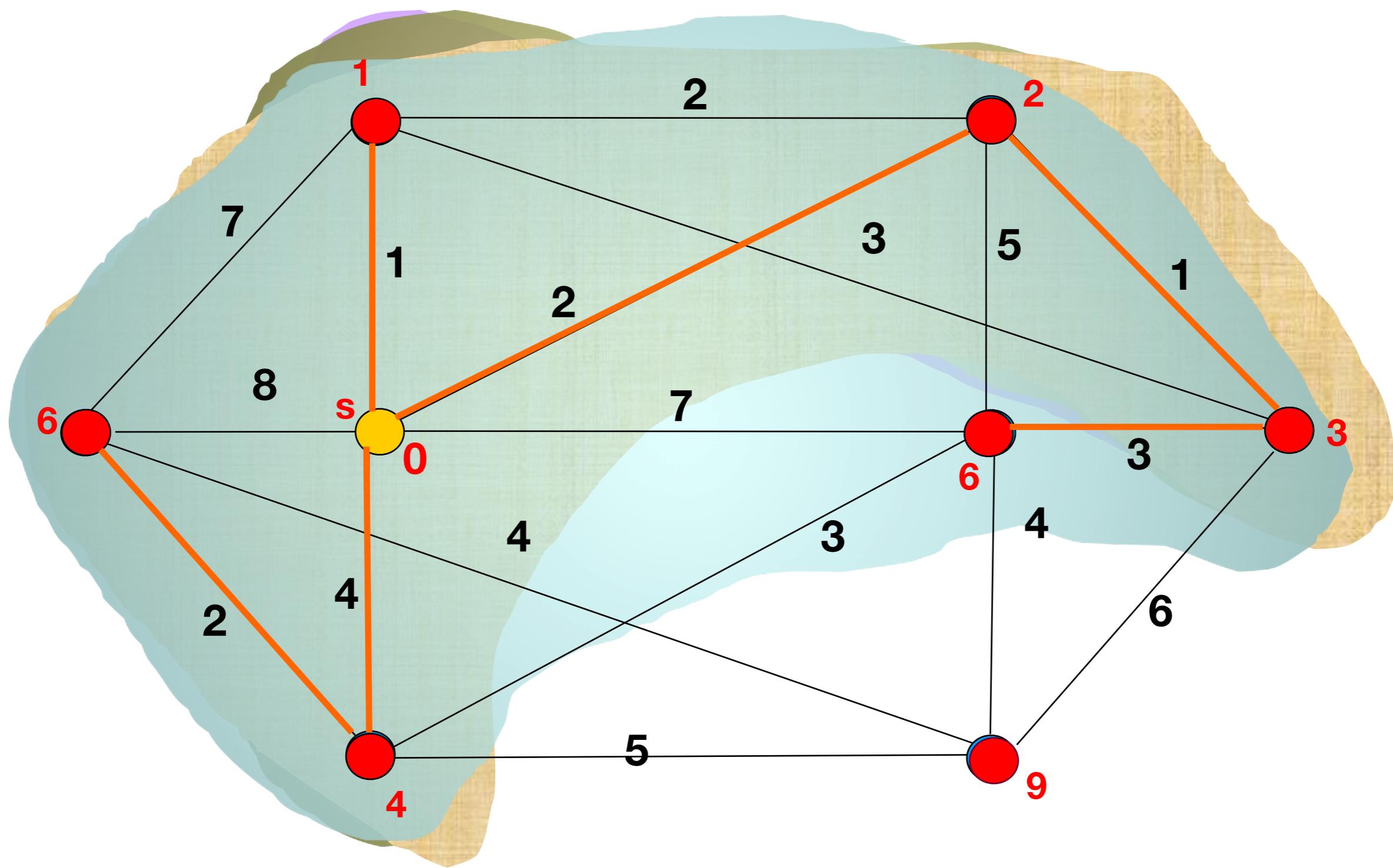
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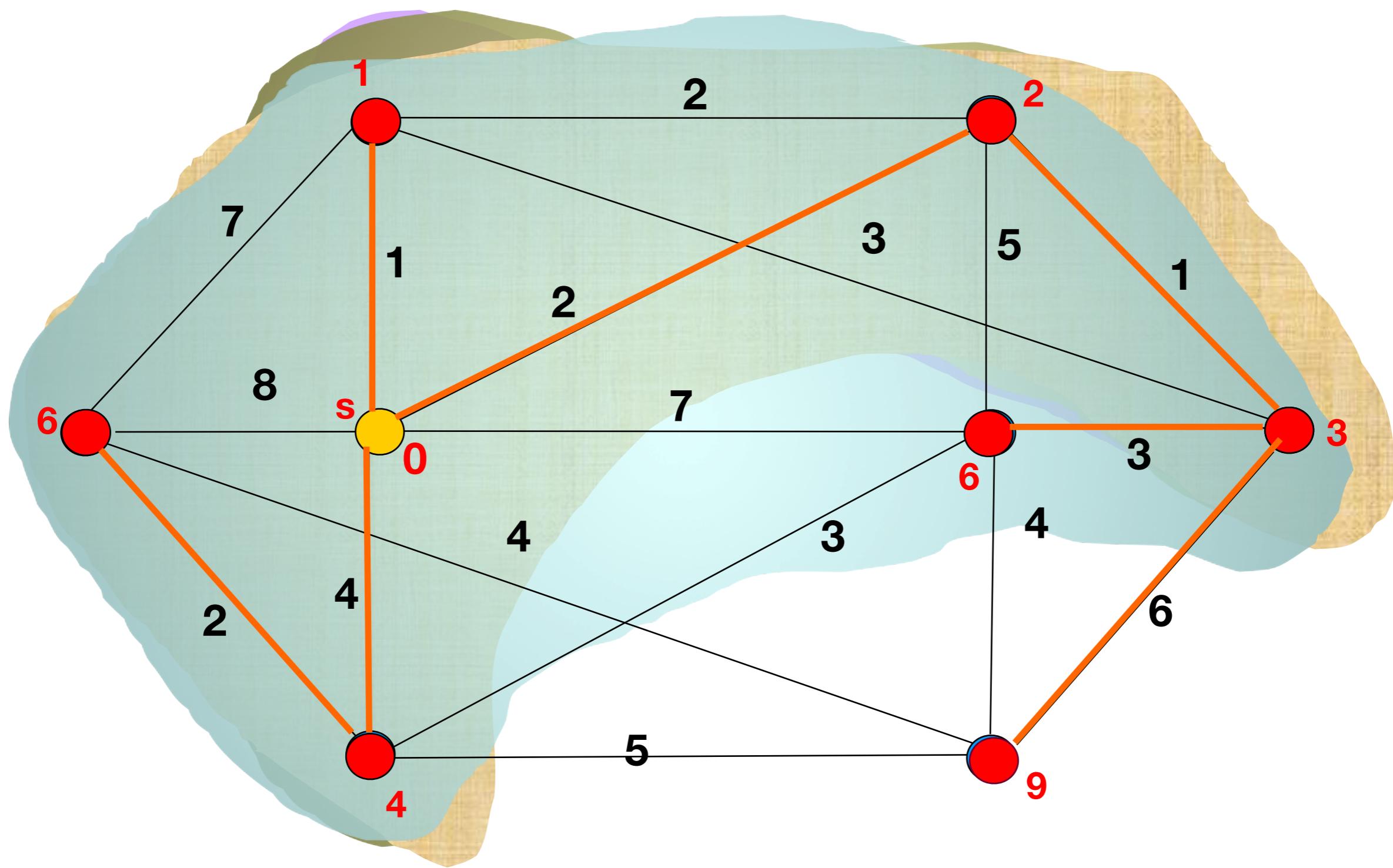
# Dijkstra's Algorithm



# Dijkstra's Algorithm



# Dijkstra's Algorithm



# Priority Queue-based Implementation

## Shortest Paths

```
Void shortestPaths(EdgeList[] adjInfo, int n, int s,  
int[] parent, float[]fringeWgt)
```

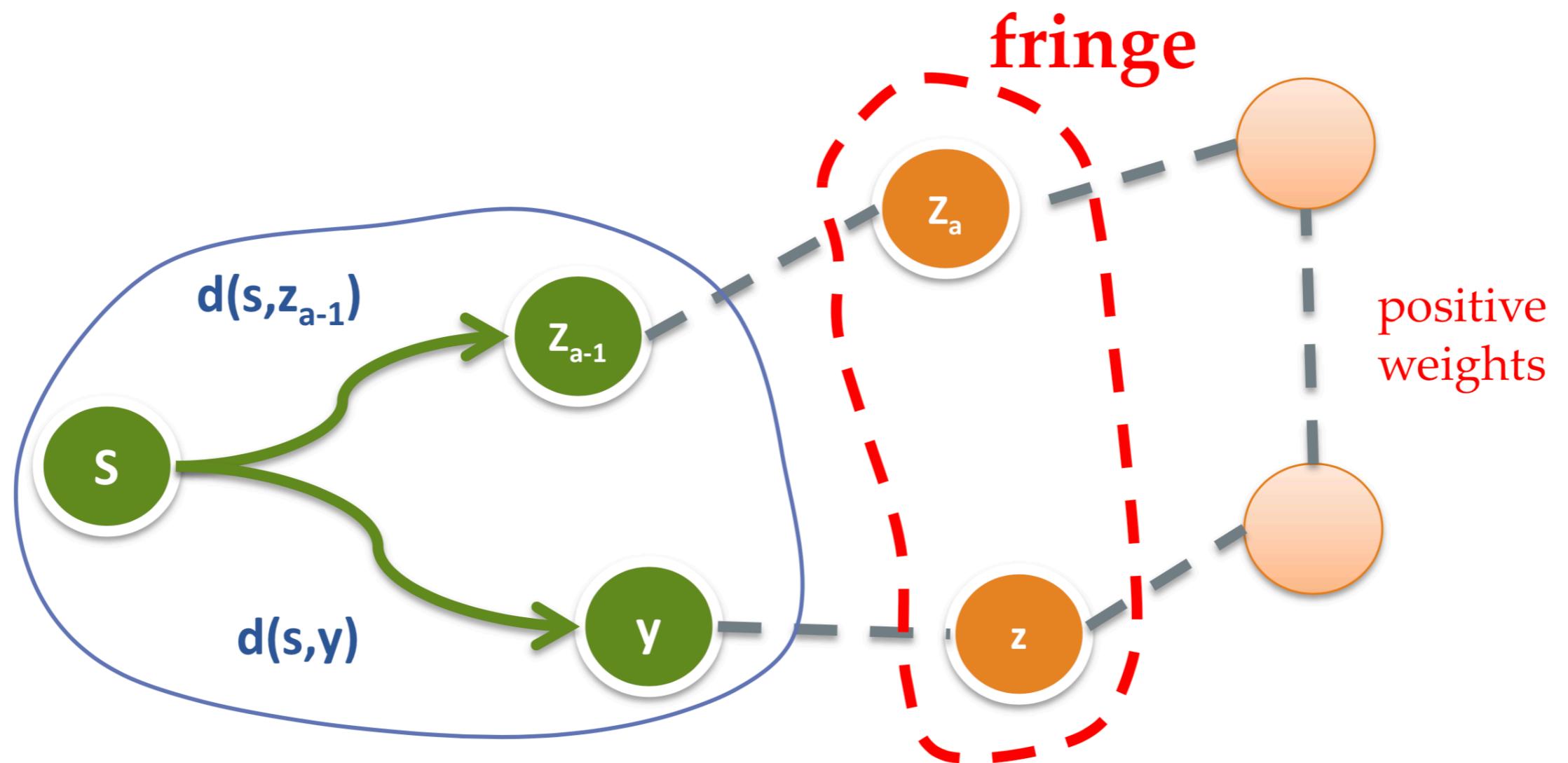
```
int[] status = new int[n+1];  
MinPQ pq = create(n, status, parent, fringeWgt);  
  
insert(pq, s, -1, 0);  
while(isEmpty(pq)==false)  
    int v = getMin(pq);  
    deleteMin(pq);  
    updateFringe(pq, adjInfo[v], v);
```



```
void updateFringe(MinPQ pq, EdgeList  
adjInfoOfV, int v)  
  
float myDist = pq.fringeWgt[v];  
EdgeList remAdj;  
remAdj = adjInfoOfV;  
while{remAdj != nil}  
    EdgeInfo wInfo = first(remAdj);  
    int w = wInfo.to;  
    float newDist = myDist + wInfo.weight;  
    if(pq.status[w]==unseen)  
        insert(pq,w,v,newDist);  
    else if(pq.status[w] = fringe)  
        if(newDist < getPriority(pq,w))  
            decreaseKey(pq,w,v,newDist);  
    remAdj = rest(remAdj);  
return;
```

# Correctness of Dijkstra Algorithm

- $W(s \rightarrow y \rightarrow z) < W(s \rightarrow z_{a-1} \rightarrow z_a \rightarrow z)$



# The Dijkstra Skeleton

- Single-source shortest path (SSSP)

- SSSP + node weight constraint

- E.g. in routing

- Each router has its cost (node cost)

- Each route has its cost (edge cost)

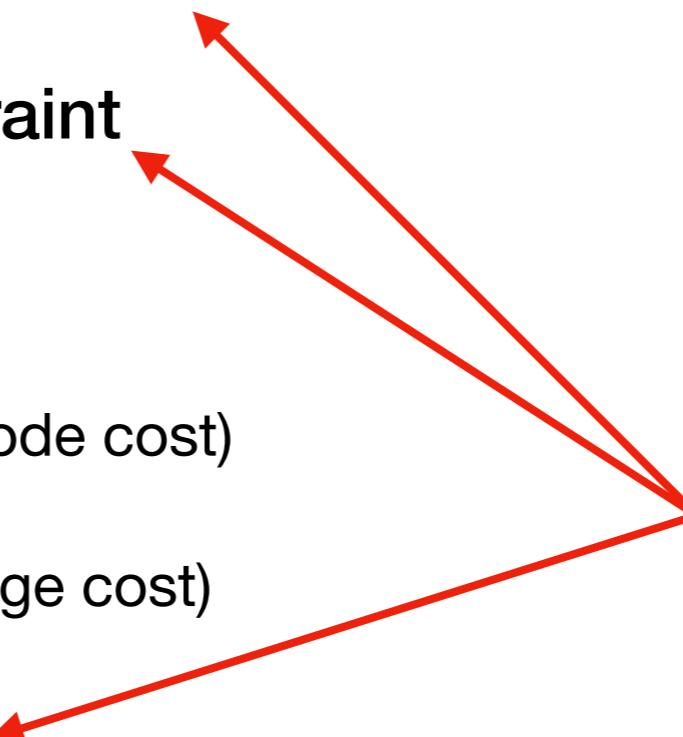
- SSP + capacity constraint

- The “pipe problem”

- Maximize the min edge weight

- The “electric vehicle problem”

- Minimize the max edge weight



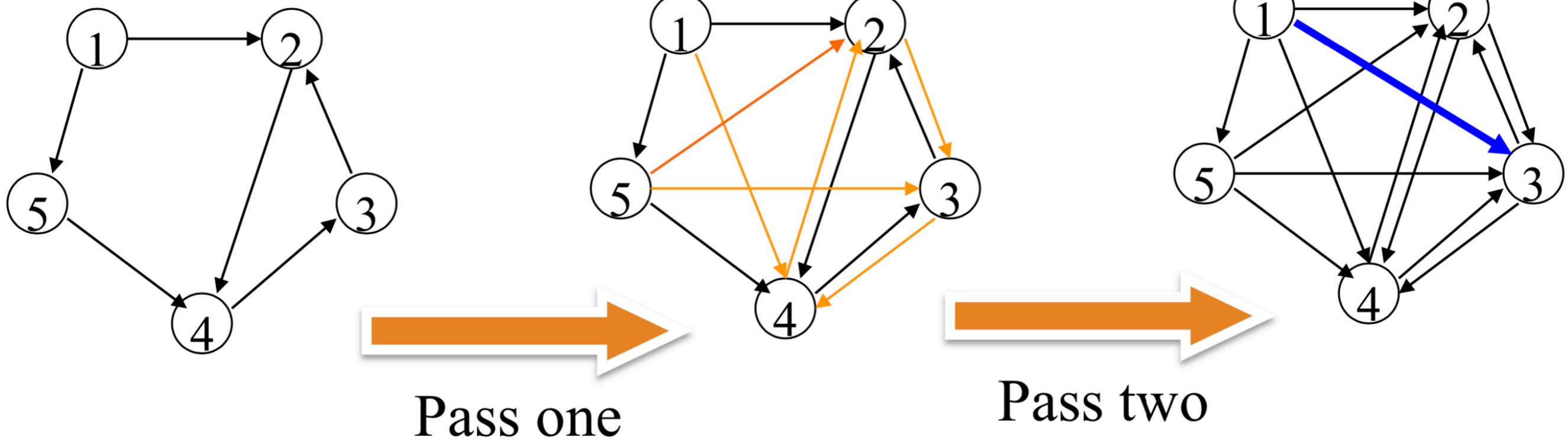
**Dijkstra Skeleton**

# All-pairs Shortest Paths

- For **all** pair of vertices in a graph, say,  $u, v$ :
  - Is there a path from  $u$  to  $v$ ?
  - What is the **shortest** path from  $u$  to  $v$ ?
- Reachability as a (reflexive) **transitive closure** of the adjacency relation
  - Which can be represented as a bit matrix

# Transitive Closure by Shortcuts

- The idea: if there are edges  $s_i s_k$ ,  $s_k s_j$ , then an edge  $s_i s_j$ , the “shortcut” is inserted.



# Shortcut Algorithm

- Input: A, an  $n \times n$  boolean matrix that represents a binary relation
- Output: R, the boolean matrix for the transitive closure of A
- Procedure

- void simpleTransitiveClosure(boolean[][] A, int n, boolean[][] R)
- int i,j,k;
- Copy A to R; **O(n<sup>4</sup>)**
- Set all main diagonal entries,  $r_{ii}$ , to true;
- while(any entry of R changed during one complete pass)
- for(i=1; i≤n; i++)
- for(j=1; j≤n; j++) ← The order of (i,j,k) matters
- for(k=1; k≤n; k++)
- $r_{ij} = r_{ij} \vee (r_{ik} \wedge r_{kj})$

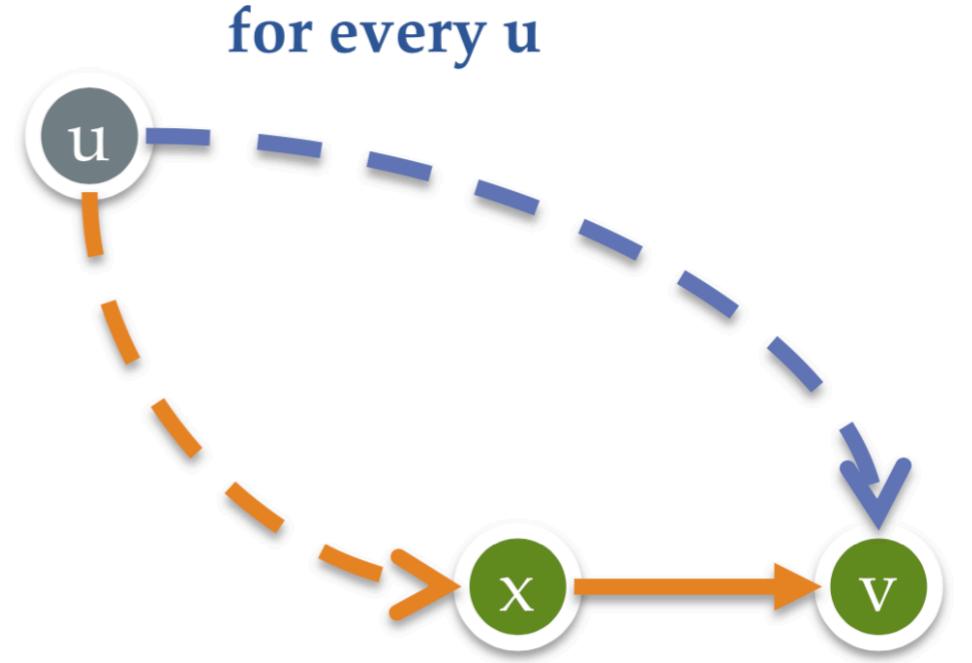
# Another Way to Add Shortcuts

- Enumerate all edges  $(x, v)$

- $v$  as the destination
- Enumerate all possible sources  $u$

while any entry of  $R$  changed  
for all vertices  $u$

for every edge  $(x, v)$       **O( $n^2m$ )**  
 $r_{uv} = r_{uv} \vee (r_{ux} \wedge r_{xv})$



**n-1 round iteration**

# Length of the Path

- Recursion

- Reachable via at most k edges

for every u

- Enumeration

- Enumerate all path length

- Enumerate all sources and destinations

for k=1 to n-1

for all vertices u

for all vertices v

for all vertices x pointing to v

$$r_{uv}^k = r_{uv}^{k-1} \vee (r_{ux}^{k-1} \wedge r_{xv})$$

$$r_{uv}=1$$

O(n<sup>4</sup>)

k-1 path

u

k path

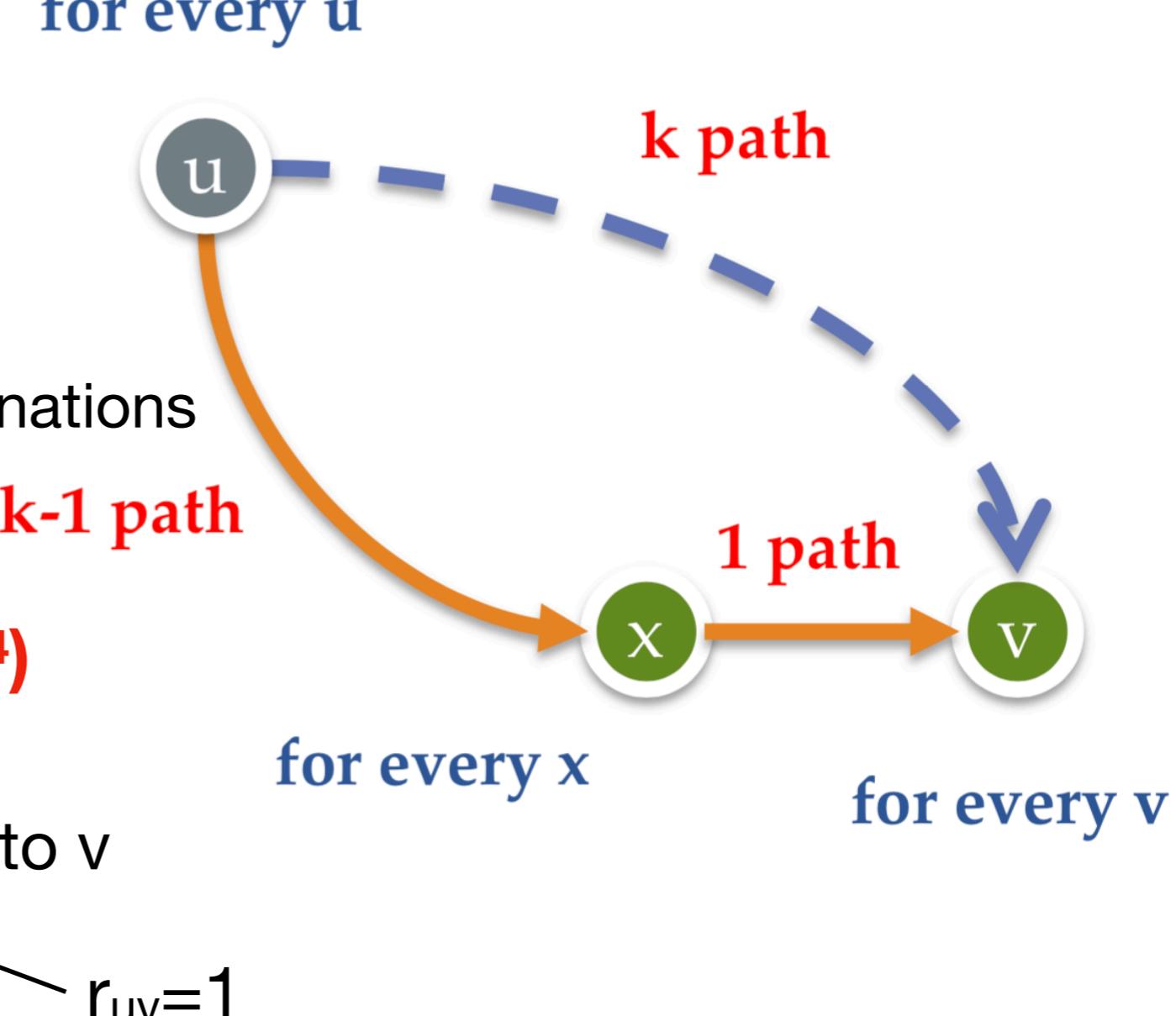
x

1 path

v

for every x

for every v

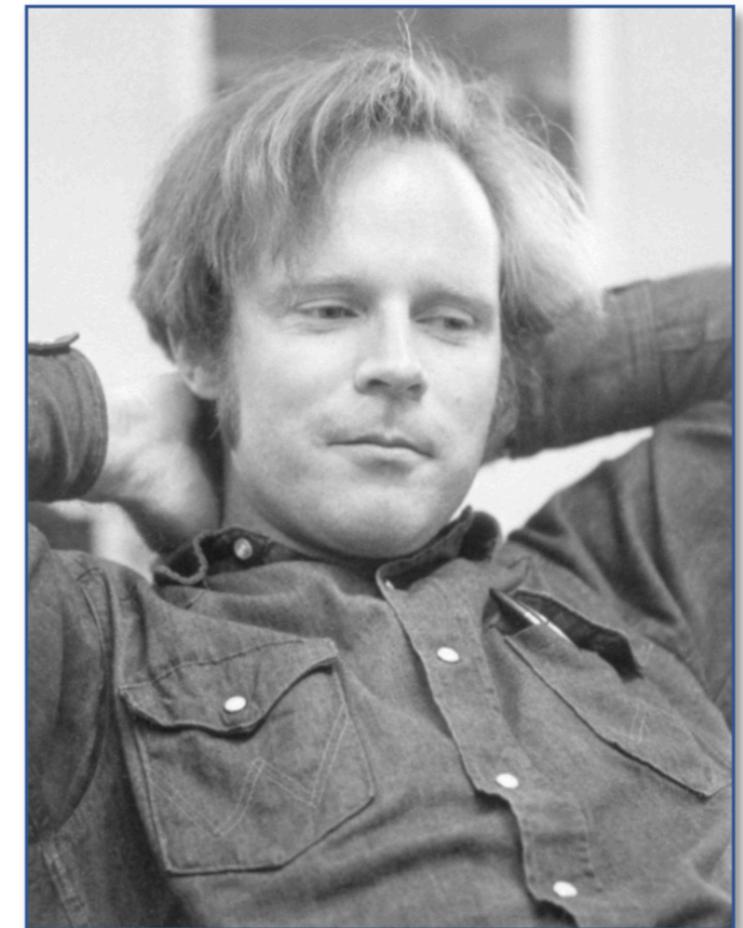


# Floyd's Lemma

组合问题的优良算法具有巨大回报，这个事实激励了技术水平的突飞猛进。... 大约从1970年起，计算机科学家们经历了所谓的‘**Floyd引理**’现象：看似需用 $n^3$ 次运算的问题实际上可能用 $O(n^2)$ 次运算就能求解，看似需用 $n^2$ 次运算的问题实际上可能用 $O(n \log n)$ 次运算就能处理，而且 $n \log n$ 通常还可以减少到 $O(n)$ 。一些更难的问题的运行时间也从 $O(2^n)$ 减少到 $O(1.5^n)$ ，再减少到 $O(1.3^n)$ ，等等。

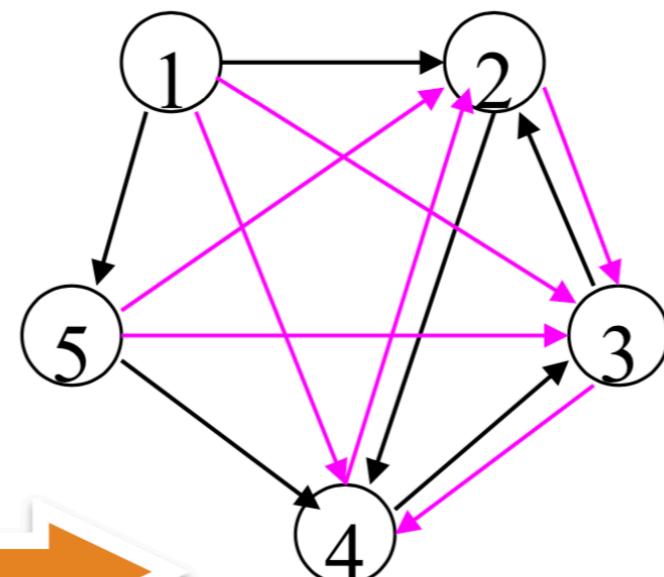
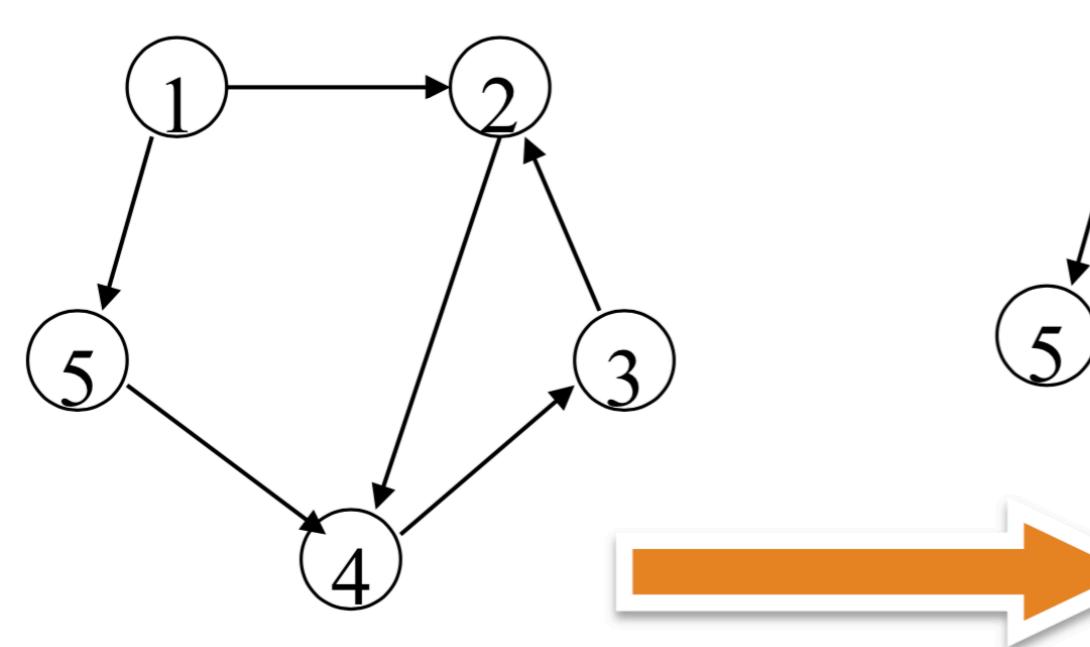
- Knuth, Volumn4A, TAOCP

Robert W Floyd, In Memoriam  
by Donald E. Knuth, Stanford University



# Shortcuts in Different Order

- Duplicated checking may be deleted by changing the order of the vertices.



Pass one

Check the vertices in decreasing order.

No edge is added in  
Pass two. End.

# Change the Order: The Warshall Algorithm

- void simpleTransitiveClosure(boolean[][] A, int n, boolean[][] R)
- int i,j,k;
- Copy A to R;
- Set all main diagonal entries,  $r_{ii}$ , to true;
- ~~while(any entry of R changed during one complete pass)~~
- **for**(k=1; k≤n; i++)
- **for**(i=1; i≤n; j++)
- **for**(j=1; j≤n; j++)
- $r_{ij} = r_{ij} \vee (r_{ik} \wedge r_{kj})$

k Varies in the  
outmost loop

Note: “false to true”  
can not be reversed

# Why the Floyd-Warshall Algorithm Works

- $\langle k, i, j \rangle$  or  $\langle i, j, k \rangle$ 
  - The order matters
  - That's why Dijkstra fails



算法青年

2014-8-4 23:18 来自 微博 weibo.com

算法没学好还真看不懂的笑话啊，赞~ // @ant\_hengxin: 信息量很大啊

@geelaw ★

再发一次我创造的一个笑话。问：为什么 Dijkstra 没有提出 Floyd 算法？答：因为他是  $ijk$  而不是  $kij$ 。

2014-8-3 22:58 来自 微博Win8客户端

120 | 12 | 7

阅读 5230 推广

5

评论

5

# Correctness of the Warshall Algorithm

- Notation:

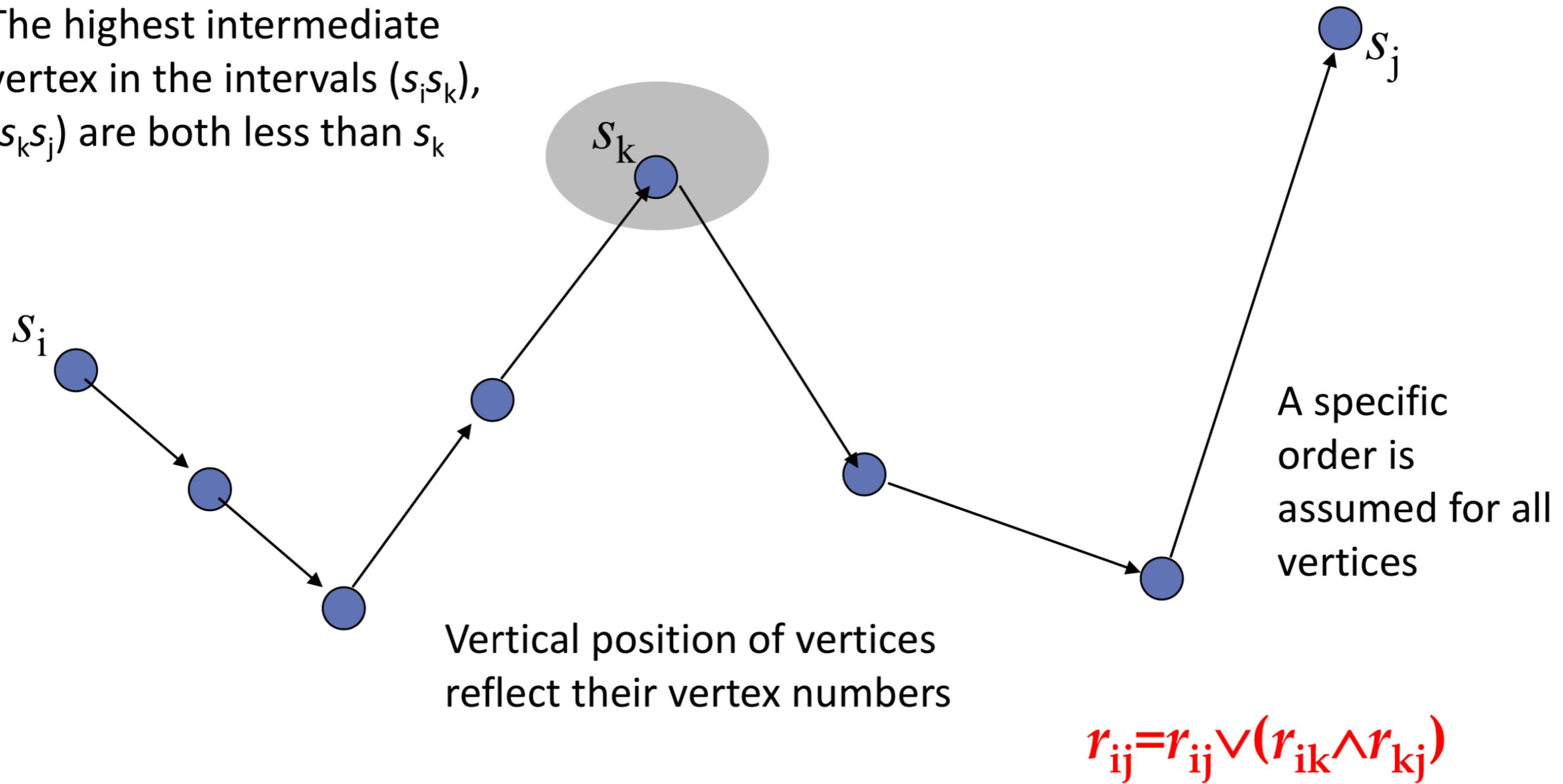
- The value of  $r_{ij}$  changes during the execution of the body of the “for k...” loop
  - After initializations:  $r_{ij}^{(0)}$
  - After the k<sup>th</sup> time of execution:  $r_{ij}^{(k)}$

# Correctness of the Warshall Algorithm

- If there is a simple path from  $s_i$  to  $s_j$  ( $i \neq j$ ) for which the highest-numbered intermediate vertex is  $s_k$ , then  $r_{ij}^{(k)} = \text{true}$ .
- Proof by induction:
  - Base case:  $r_{ij}^{(0)} = \text{true}$  if and only if  $s_i s_j \in E$
  - Hypothesis: the conclusion holds for  $h < k$  ( $h \geq 0$ )
  - Induction: the simple  $s_i s_j$ -path can be looked as  $s_i s_k$ -path +  $s_k s_j$ -path, with the indices  $h_1, h_2$  of the highest-numbered intermediate vertices of both segment **strictly (simple path)** less than  $k$ . So,  $r_{ik}^{(h1)} = \text{true}$ ,  $r_{kj}^{(h2)} = \text{true}$ , then  $r_{ik}^{(k-1)} = \text{true}$ ,  $r_{kj}^{(k-1)} = \text{true}$  (Remember, false to true can not be reversed). So,  $r_{ij}^{(k)} = \text{true}$

# Highest-numbered Intermediate Vertex

The highest intermediate vertex in the intervals  $(s_i s_k)$ ,  $(s_k s_j)$  are both less than  $s_k$



# Correctness of the Warshall Algorithm

- If  $r_{ij}^{(k)}$ =true, then there is a  $(s_i, s_j)^{(k)}$  path
- Proof
  - If  $r_{ij}^{(0)}$ =true, then there is  $(s_i, s_j)^{(0)}$  path
  - If  $r_{ij}$  first become true in round k, then
    - $r_{ik}^{(k-1)} = \text{true}$ ,  $r_{kj}^{(k-1)} = \text{true}$
    - We have a “ $s_i \rightarrow s_k \rightarrow s_j$ ” path
      - Intermediate nodes in  $\{1, 2, \dots, k-1\} \cup \{k\}$

# All-pairs Shortest Paths

- Shortest path property

- If a shortest path from  $x$  to  $z$  consisting of path  $P$  from  $x$  to  $y$  followed by path  $Q$  from  $y$  to  $z$ . Then  $P$  is a shortest  $xy$ -path, and  $Q$ , a shortest  $yz$ -path.
- The regular matrix representing a graph can easily be transformed into a (minimum) distance matrix  $D$

(just replacing 1 by edge weight, 0 by infinity, and setting main diagonal elements as 0)

# Computing the Distance Matrix

- Basic formula:

- $D^{(0)}[i][j] = w_{ij}$
- $D^{(k)}[i][j] = \min(D^{(k-1)}[i][j], D^{(k-1)}[i][k] + D^{(k-1)}[k][j])$

- Basic property:

- $D^{(k)}[i][j] = d_{ij}^{(k)}$
- where  $d_{ij}^{(k)}$  is the weight of a shortest path from  $v_i$  to  $v_j$  with highest numbered intermediate vertex  $v_k$ .

# All-pairs Shortest Paths

- Floyd algorithm
  - Only slight changes on Washall's algorithm.

```
Void allPairsShortestPaths(float [][] W, int n, float [][] D)
    int i, j, k;
    Copy W into D;
    for (k=1; k≤n; k++)
        for (i=1; i≤n; i++)
            for (j=1; j≤n; j++)
                D[i][j] = min (D[i][j], D[i][k]+D[k][j]);
```

# All-pairs Shortest Paths

- Construction of the routing table

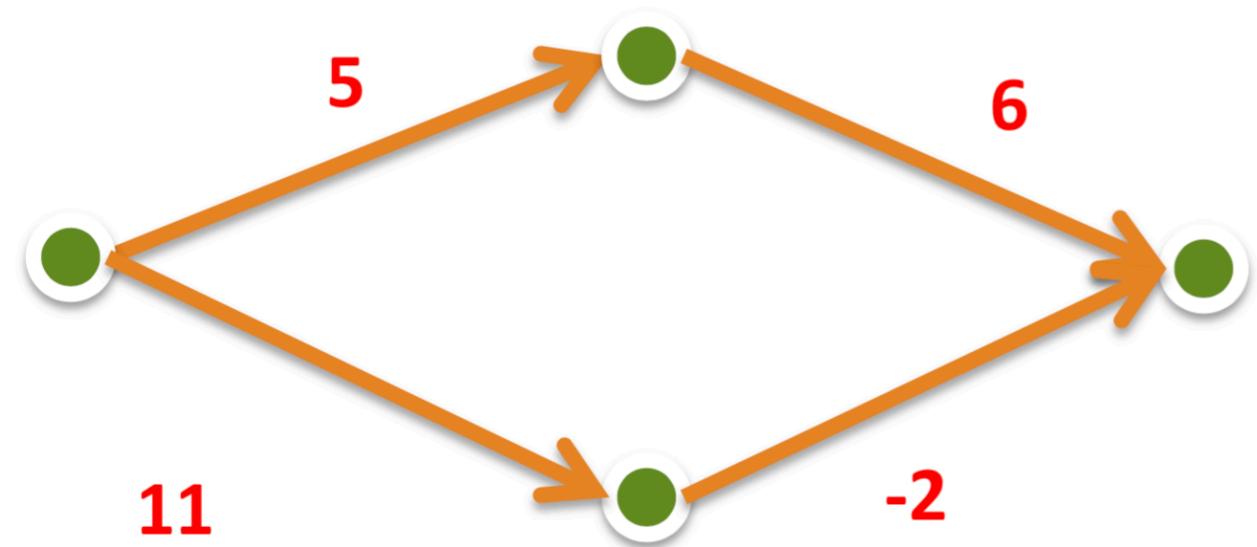
- Forward, backward

- APSP + capacity constraints

- The pipeline problem
  - The electric vehicle problem

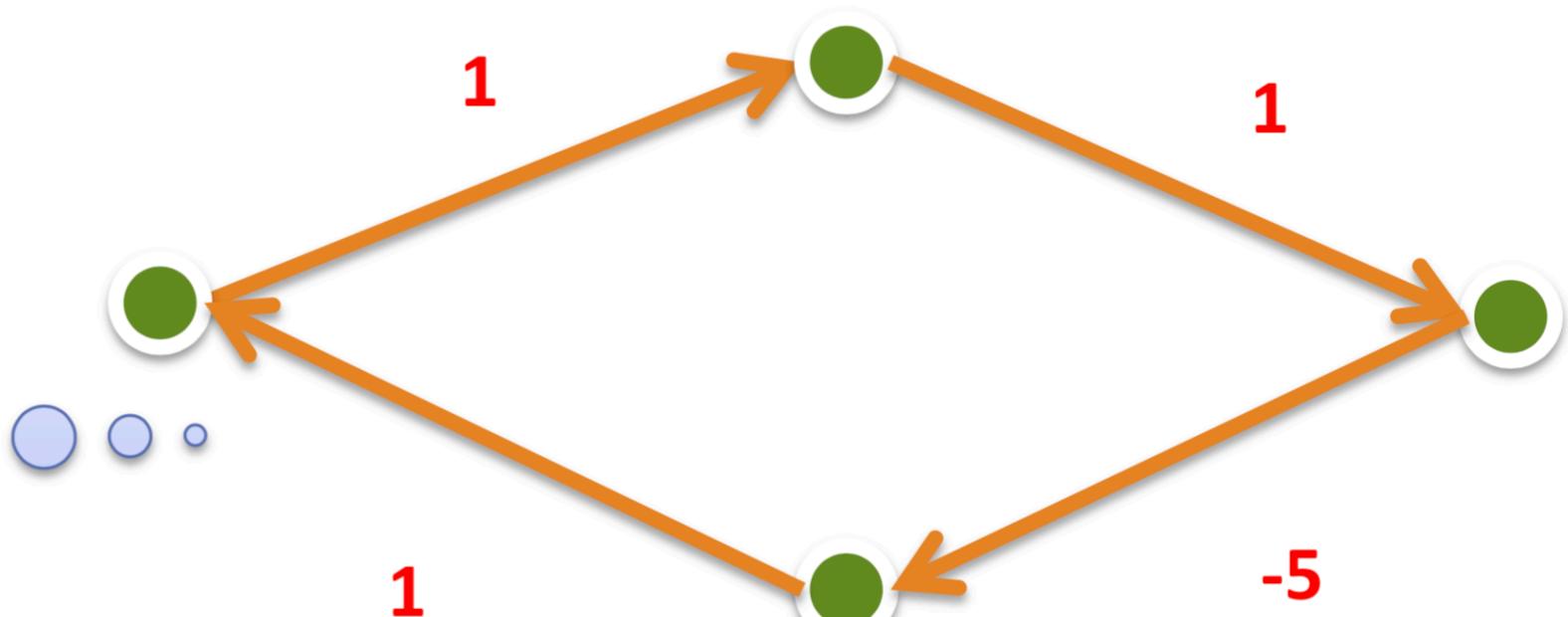
**Floyd algorithm => Floyd skeleton**

# Negative Weight



“shortest path” is not well defined

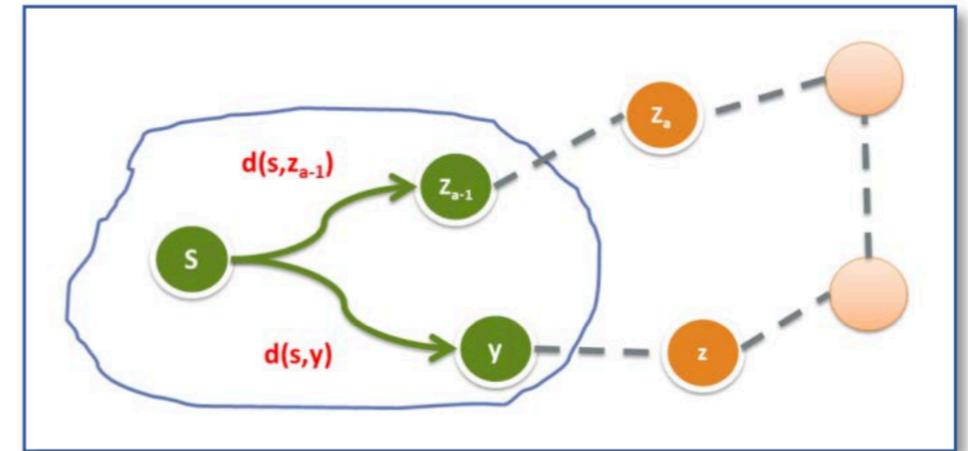
Negative weight cycle



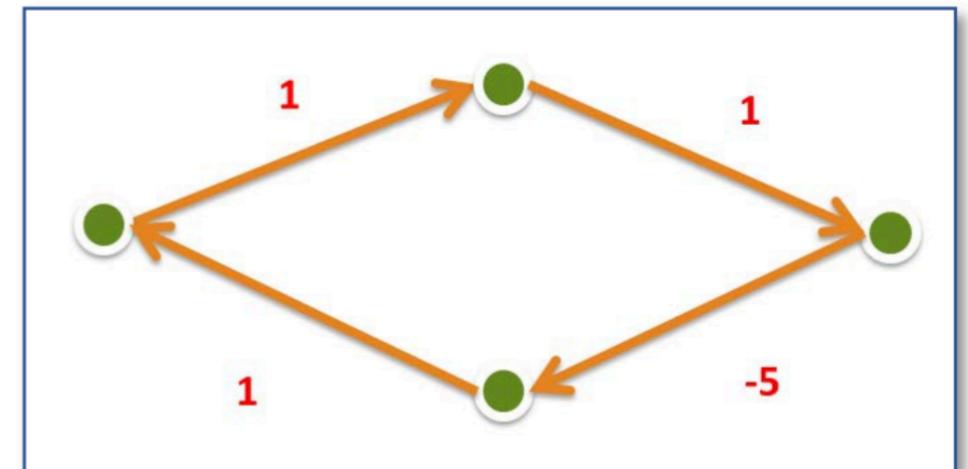
# Negative Weight

- Can the shortest path algorithm work correctly?

- Dijkstra's algorithm
  - No negative weight edge



- Floyd's algorithm
  - No negative weight cycle



# Matrix Representation

- Define family of matrix  $A^{(p)}$ :
  - $a_{ij}^{(p)} = \text{true}$  if and only if there is a path of length  $p$  from  $s_i$  to  $s_j$ .
  - $A^{(0)}$  is specified as identity matrix.  $A^{(1)}$  is exactly the adjacency matrix.
  - Note that  $a_{ij}^{(2)} = \text{true}$  if and only if exists some  $s_k$ , such that both  $a_{ik}^{(1)}$  and  $a_{kj}^{(1)}$  are true. So,  $a_{ij}^{(2)} = \vee_{k=1,2,\dots,n} (a_{ik}^{(1)} \wedge a_{kj}^{(1)})$ , which is an entry in the *Boolean matrix product*.

# Boolean Matrix Operations

- Boolean matrix product  $C=AB$  as:

- $c_{ij} = \vee_{k=1,2,\dots,n} (a_{ik} \wedge b_{kj})$

- Boolean matrix sum  $D=A+B$  as:

- $d_{ij} = a_{ij} \vee b_{ij}$

- $R$ , the transitive closure matrix of  $A$ , is the sum of all  $A^p$ ,  $p$  is a non-negative integer.

- For a digraph with  $n$  vertices, the length of the longest simple path is no larger than  $n-1$ .

# Bit Matrix

- A **bit string** of length  $n$  is a sequence of  $n$  bits occupying contiguous storage(word boundary)  
(usually,  $n$  is larger than the word length of a computer)
- If  $A$  is a **bit matrix** of  $n \times n$ , then  $A[i]$  denotes the  $i$ th row of  $A$  which is a bit string of length  $n$ .  $a_{ij}$  is the  $j$ th bit of  $A[i]$ .
- The **procedure** **bitwiseOR(a,b,n)** compute  $a \vee b$  bitwise for  $n$  bits, leaving the result in  $a$ .

# Straightforward Multiplication of Bit Matrix

## ● Computing $C=AB$

- <Initialize C to the zero matrix>
- **for** ( $i=1$ ;  $i \leq n$ ,  $i++$ )
- **for** ( $k=1$ ;  $k \leq n$ ,  $k++$ )
- **if** ( $a_{ik} == \text{true}$ ) **bitwiseOR**( $C[i]$ ,  $B[k]$ ,  $n$ )

Thought as a union of sets (row union),  $n^2$  unions are done at most

In the case of  $a_{ik}$  is true,  $c_{ij} = a_{ik} b_{kj}$  is true iff.  $b_{kj}$  is true. As a result:  
 $C[i] = \cup_{k \in A[i]} B[k]$ , ( $A[i] = \{k | a_{ik} = \text{true}\}$ )

Union for  $B[k]$  is repeated each time when the kth bit is true in a different row of A is encountered.

# Reducing the Duplicates by Grouping

- Multiplication of A, B, two  $12 \times 12$  matrices

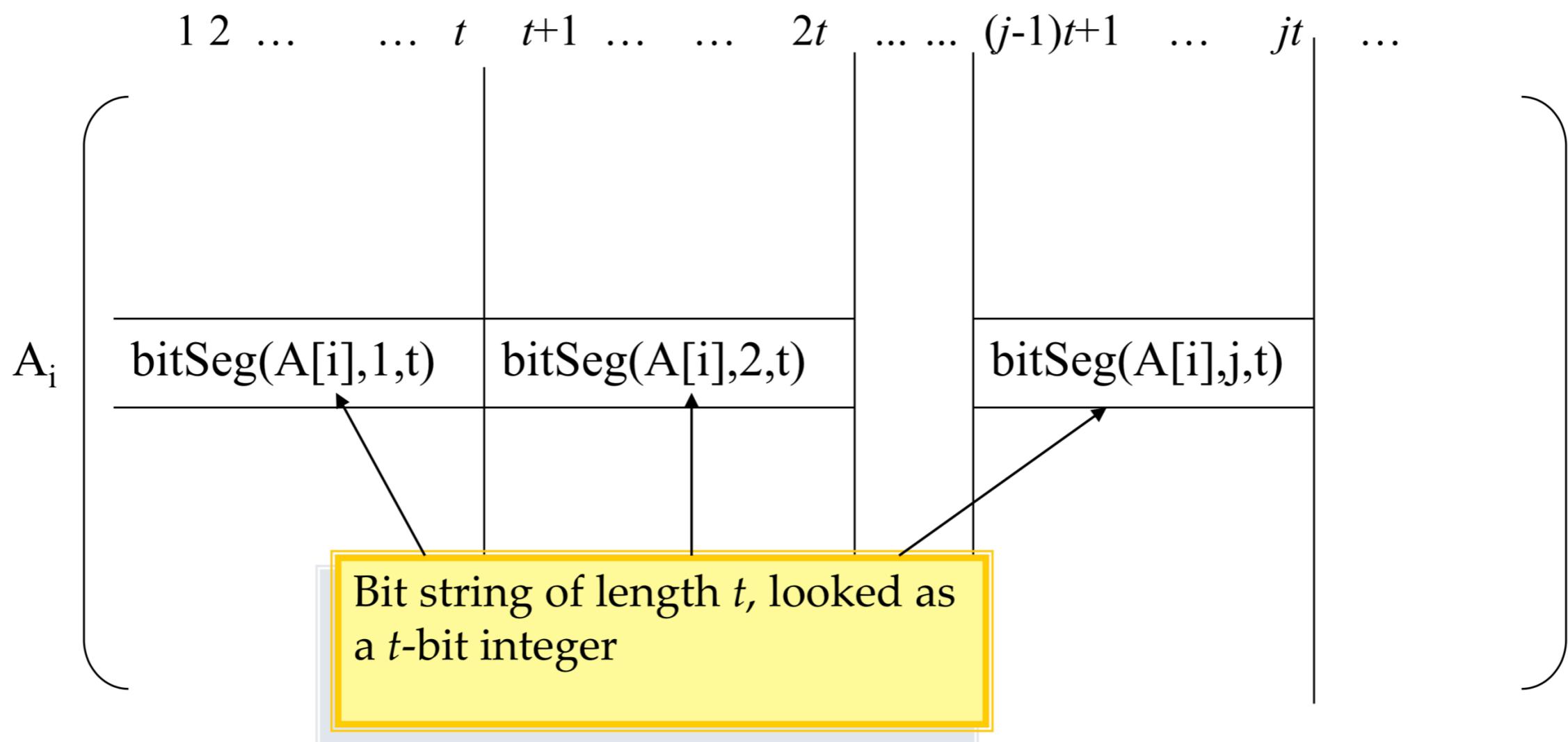
$A_1$	1 0 1 1	0 1 0 1 0 0 0 1
$A_2$	1 0 1 1	1 0 0 1 1 0 1 1
$A_3$	1 0 1 1	0 1 0 1
$A_4$	1 0 1 1	1 0 0 1 1 1 1 0
$A_5$		
$A_6$		
$A_7$		
$A_8$		
$A_9$		
$A_{10}$		
$A_{11}$		
$A_{12}$		

Segment Length t

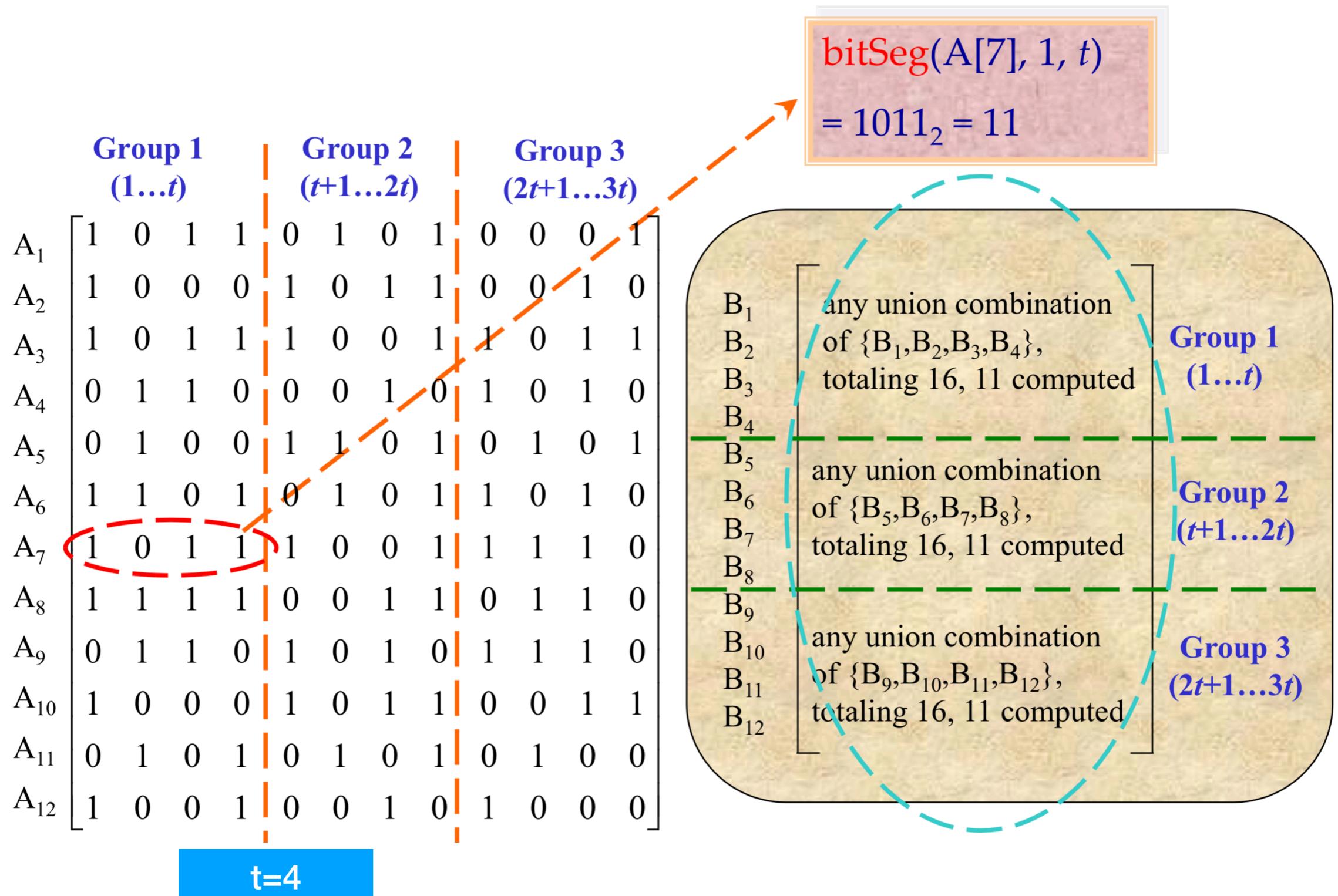
- 12 rows of  $B$  are divided evenly into 3 groups, with rows 1-4 in group 1, etc.
- With each group, all possible unions of different rows are pre-computed.  
(This can be done with 11 unions if suitable order is assumed.)
- When the first row of  $AB$  is computed,  $(B[1] \cup B[3] \cup B[4])$  is used instead of 3 different unions, and this combination is used in computing the 3<sup>rd</sup> and 7<sup>th</sup> rows as well.

# The Segmentation for Matrix A

The  $n \times n$  array



# An Example



# Storage of the Row Combinations

- Using one large 2-dimensional array
- Goals
  - keep all unions generated
  - provide indexing for using
- Coding with in a group
  - One-to-one correspondence between a bit string of length  $t$  and one union for a subset of a set of  $t$  elements
- Establishing indexing for union required
  - When constructing a row of  $AB$ , a segment can be notated as a integer. Use it as index.

# Storage the Unions

allUnion

one row for  
one group

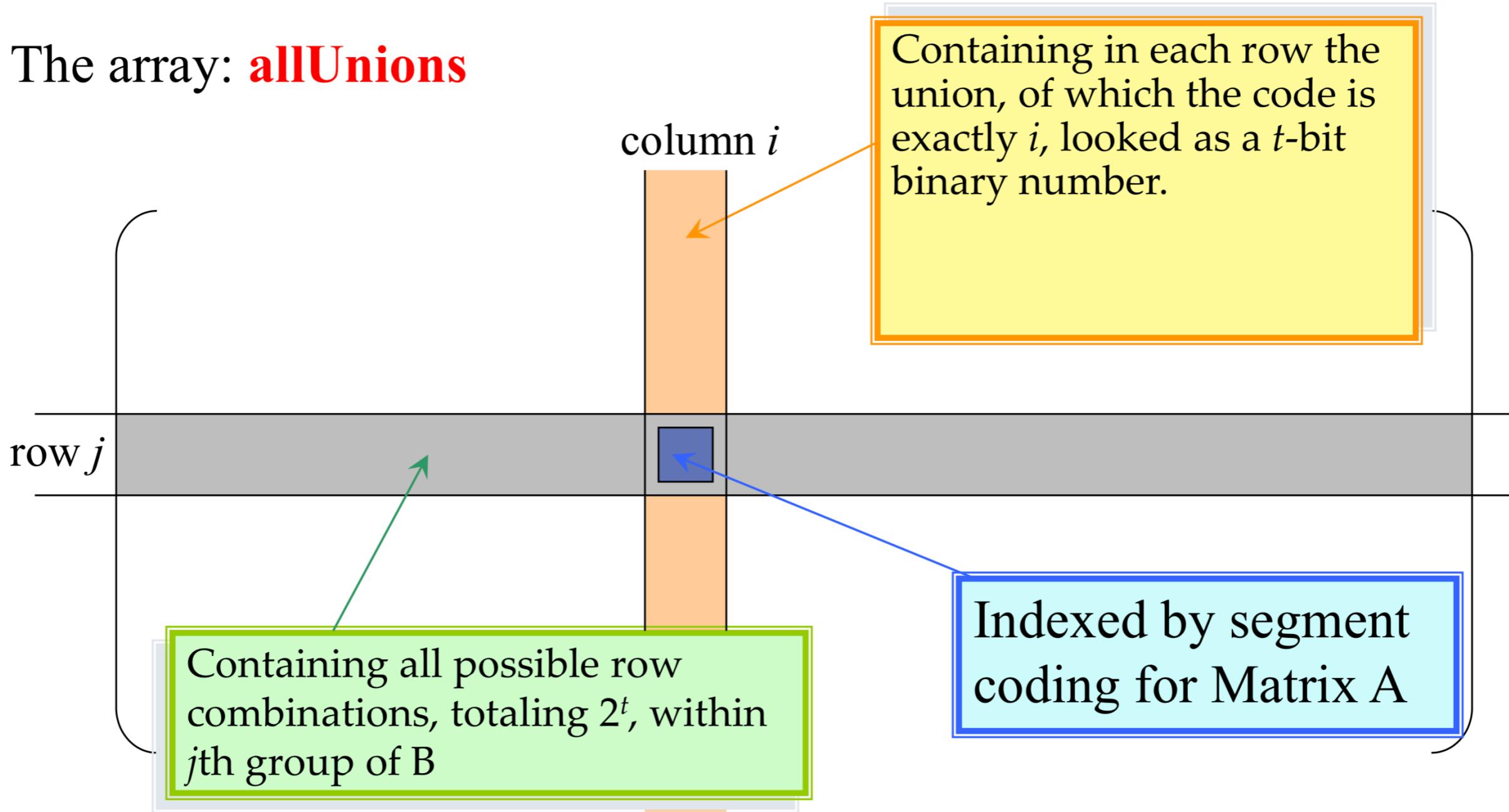
column indexed by  $\text{bitSeg}(A[i], j, t)$

$\phi$	4	3	3,4	2	2,4	2,3	2,3,4	1	1,4	1,3	1,3,4	1,2	(1,2,4)	1,2,3	1,2,3,4
$\phi$	8	7	7,8	6	6,8										
$\phi$	12	11	11,12	10	10,12										

$i, j, k$  stands for  $B_i \cup B_j \cup B_k$

# Array for Row Combinations

The array: **allUnions**



# Cost as Function of Group Size

- Cost for the pre-computation

- There are  $2^t$  different combination of rows in one group, including an empty and  $t$  singleton. Note, in a suitable order, each combination can be made using only one union. So, the total number of union is  $\textcolor{red}{g[2^t-(t+1)]}$ , where  $g=n/t$  is the number of group.

- Cost for the generation of the product

- In computing one of  $n$  rows of  $AB$ , at most one combination from each group is used. So, the total number of union is  $\textcolor{red}{n(g-1)}$

# Selecting Best Group Size

- The total number of union done is:
  - $g[2^t - (t+1)] + n(g-1) \approx (n2^t)/t + n^2/t$  (Note:  $g=n/t$ )
- Trying to minimize the number of union
  - Assuming that the first term is of higher order:
    - Then  $t \geq \lg n$ , and the least value is reached when  $t = \lg n$ .
  - Assuming that the second term is of higher order:
    - Then  $t \leq \lg n$ , and the least value is reached when  $t = \lg n$ .
- So, when  $t \approx \lg n$ , the number of union is roughly  $2n^2/\lg n$ , which is of lower order than  $n^2$ . We use  $t = \lfloor \lg n \rfloor$

# Sketch for the Procedure

- $t = \lceil \lg n \rceil$ ;  $g = \lceil n/t \rceil$ ;
- <Compute and store in **allUnions** unions of all combinations of rows of  $B$ >
- for ( $i=1$ ;  $i \leq n$ ;  $i++$ )
  - <Initialize  $C[i]$  to 0>
  - for ( $j=1$ ;  $j \leq g$ ;  $j++$ )
    - $C[i] = C[i] \cup \text{allUnions}[j][\text{bitSeg}(A[i], j, t)]$

# Kronrod Algorithm

- Input: A,B and n, where A and B are  $n \times n$  bit matrices.
- Output: C, the Boolean matrix product.
- Procedure
  - The processing order has been changed, from “row by row” to “group by group”, resulting the reduction of storage space for unions.

# Complexity of the Kronrod Algorithm

- For computing all unions within a group,  $2^t - 1$  union operations are done.
- One union is bitwiseOR'ed to  $n$  row of C
- So, altogether,  $(n/t)(2^t - 1 + n)$  row unions are done.
- The cost of row union is  $[n/w]$  bitwise or operations, where  $w$  is word size of bitwise or instruction dependent constant.

**Thank you!**  
**Q & A**