

CSCI 232:

Data Structures and Algorithms

Graphs (Traversal and Searching)

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Spring 2024

Announcements

Lab 8 on Friday

→ Short survey... should be free points for you

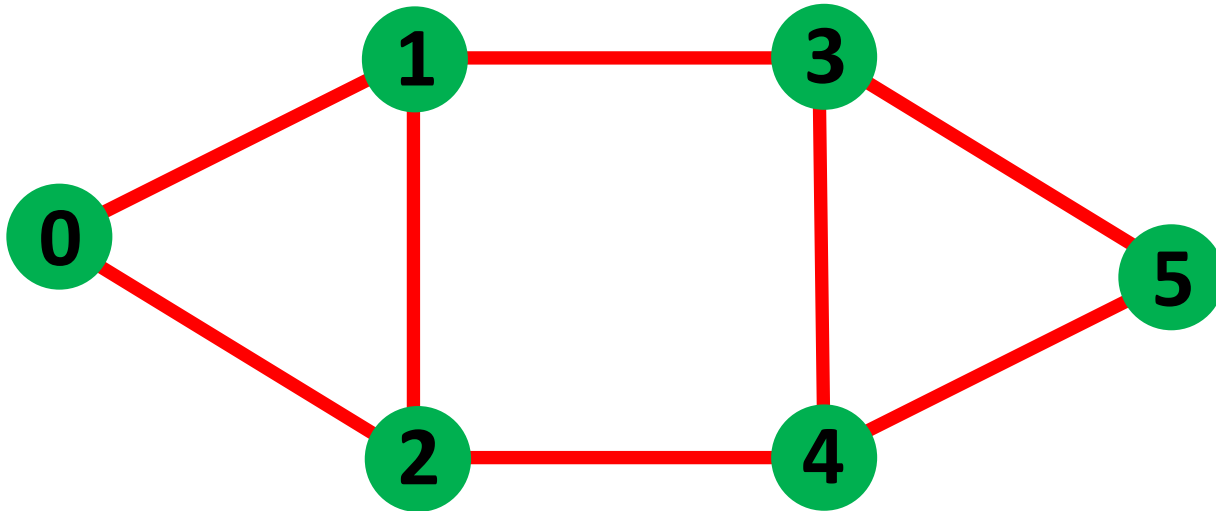
Next class (April 2nd) will be an asynchronous lecture (I'll post a lecture recording but no in-person lecture)

First portion of Program 3 is posted

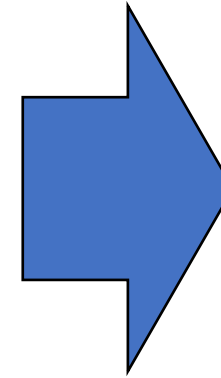
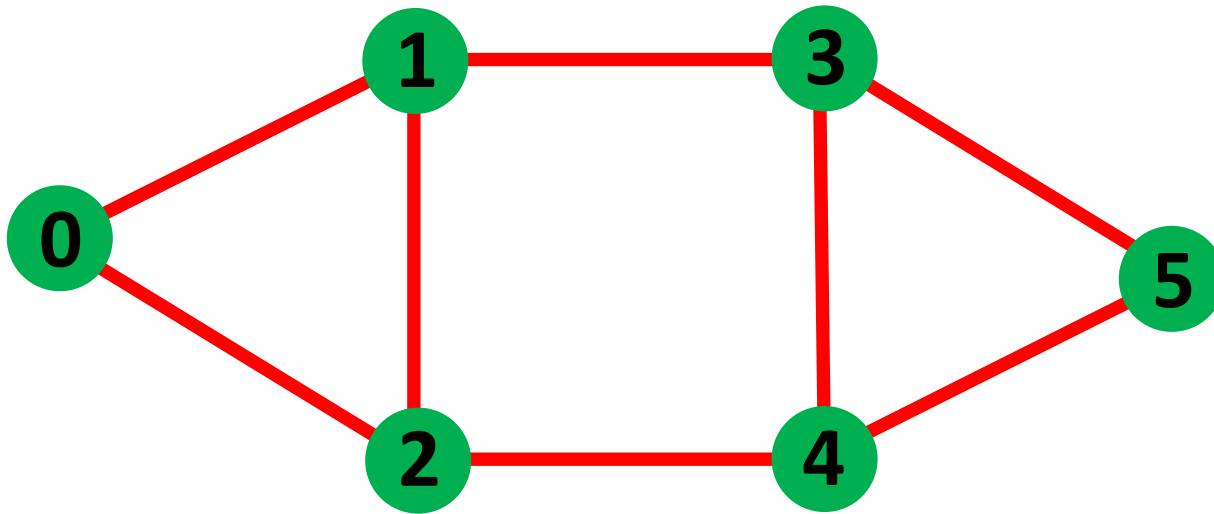
Graphs

$$G = (V, E)$$

TREE	GRAPH
There exists a hierarchical structure, and the top node is called the root node.	The concept of hierarchy leading to a unique root node does not apply here.
Is an acyclic graph.	Cycles can exist.
Must be a connected graph.	Isn't necessarily a connected graph.
Data representation is similar to a tree, with concepts like branches, roots, and leaf nodes.	Data representation is similar to a network
Applications: decision trees, implementing heaps to find max/min numbers, sorting.	Applications: Finding shortest path, navigation, route optimization.



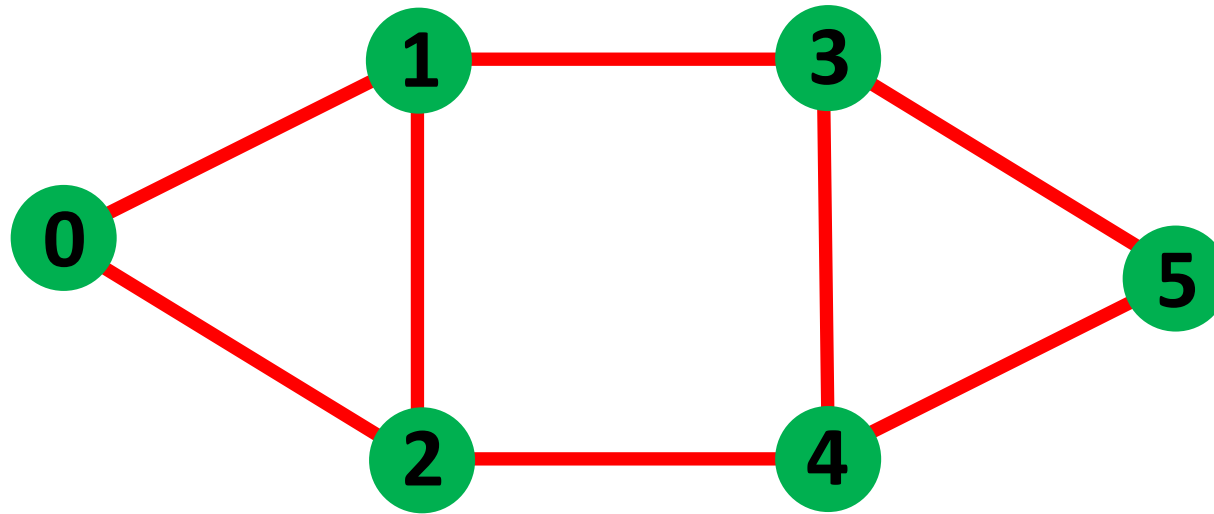
Graphs



Adjacency List

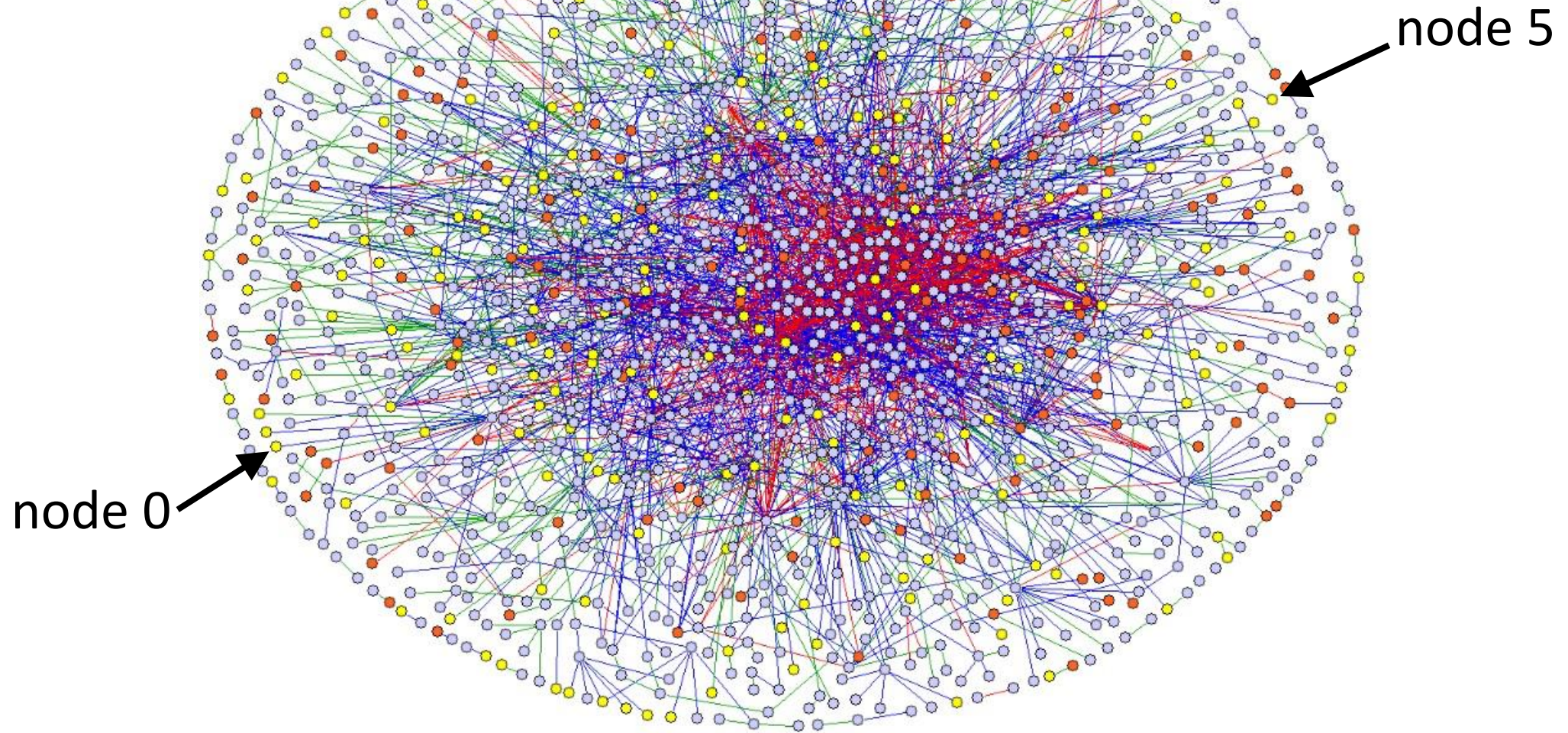
0	→	{1,2}
1	→	{0,2,3}
2	→	{0,1,4}
3	→	{1,4,5}
4	→	{2,3,5}
5	→	{3,4}

Graphs - Paths



Is there a path from node 0 to node 5?

Graphs - Paths



Is there a path from node 0 to node 5?

Graphs - Paths

0	→	{1,2}
1	→	{0,2,3}
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Is there a path from node 0 to node 5?

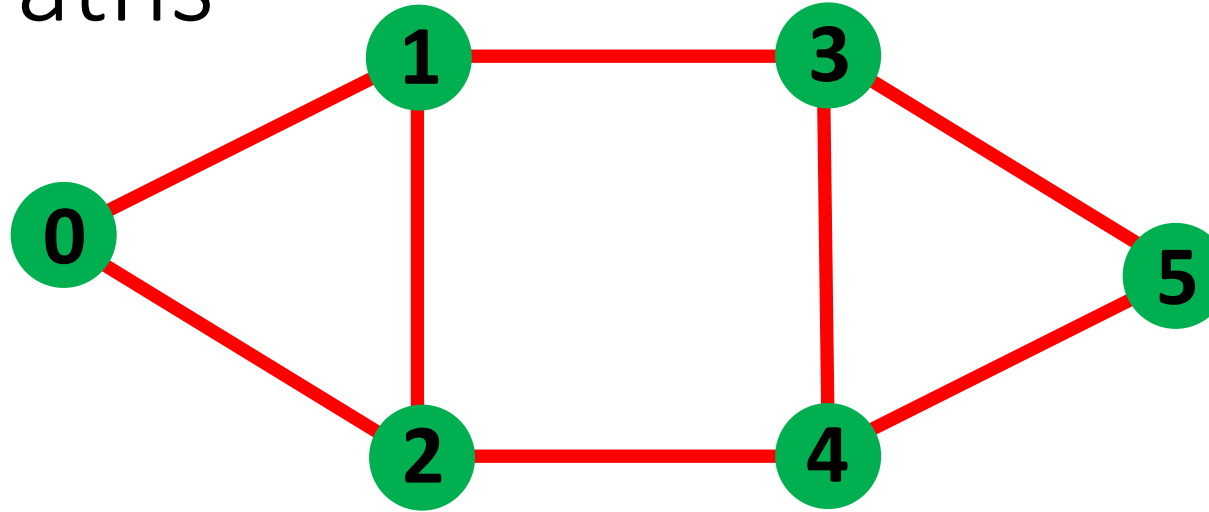
Graphs - Paths

0	→	{1,2}
1	→	{0,2,3}
2	→	{0,1,4}
3	→	{1,4,5}
4	→	{2,3,5}
5	→	{3,4}

We need a better process than “eyeballing it” for finding paths.

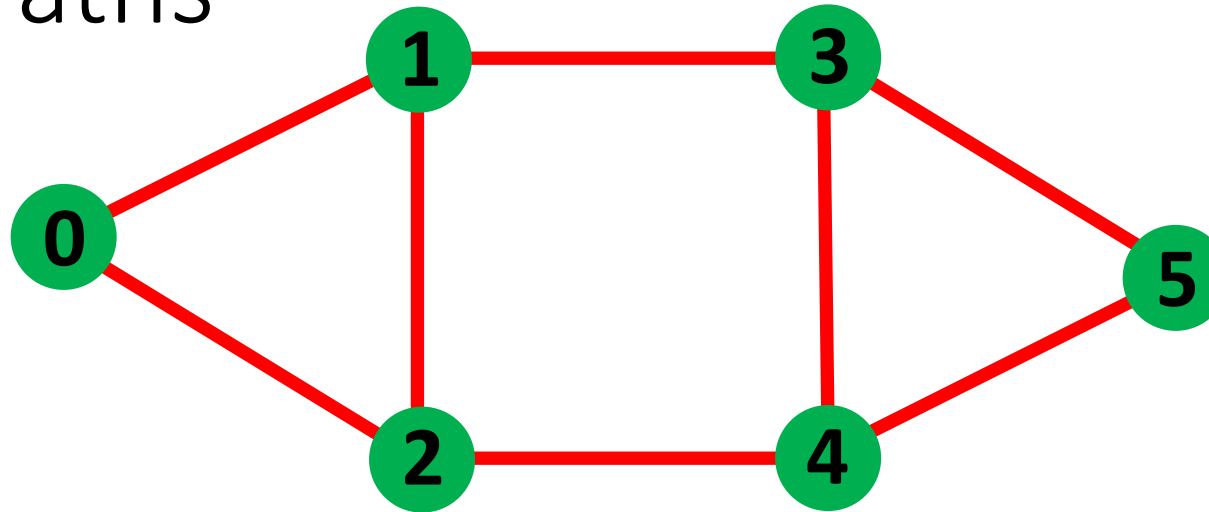
Is there a path from node 0 to node 5?

Graphs - Paths



What is a generalizable process to see if there is a path from node 0 to node 5?

Graphs - Paths



What is a generalizable process to see if there is a path from node 0 to node 5?

Start at node 0.

Go to each neighbor.

Check each neighbor's neighbor.

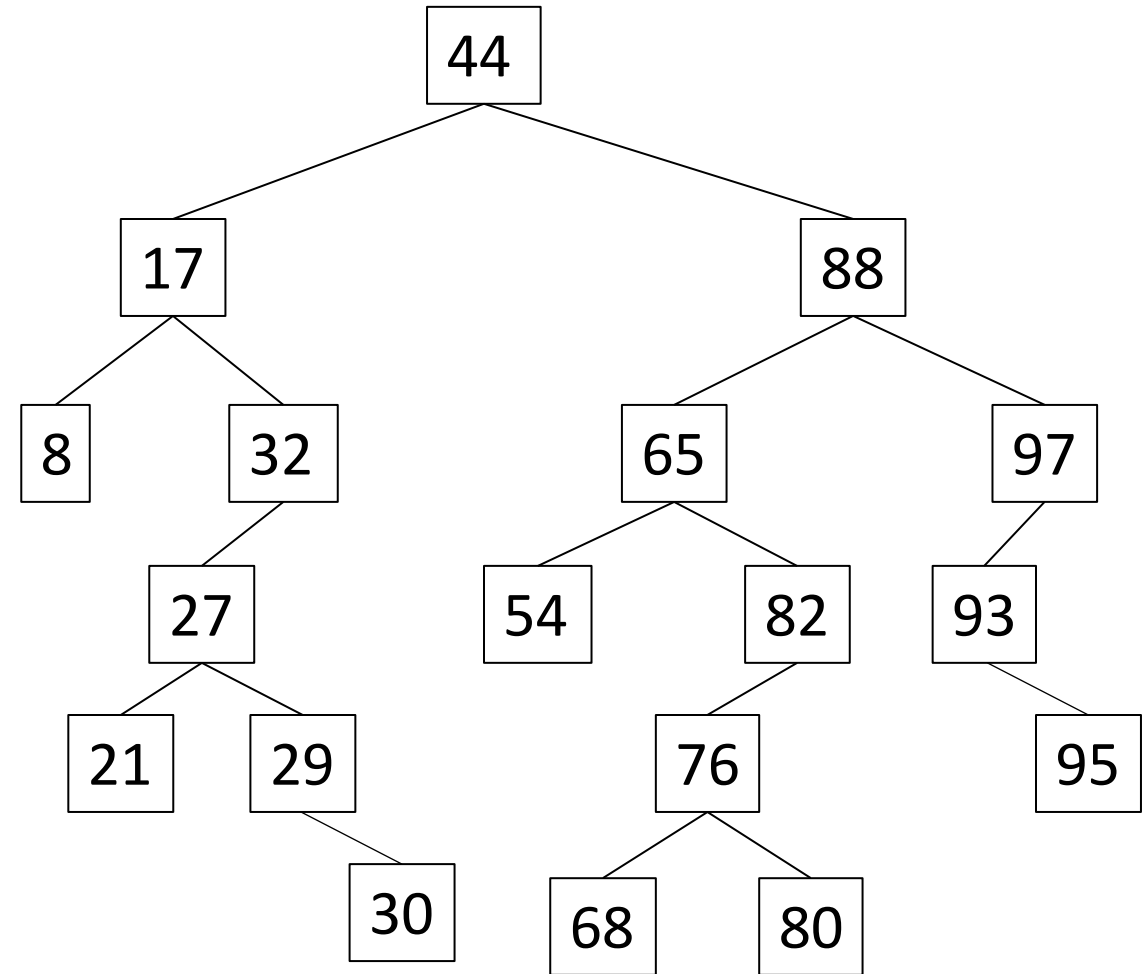
Check each neighbor's neighbor's neighbor....

Binary Search Tree - Traversal

```
public void depthFirst(Node n) {  
    if (n != null) {  
        System.out.println(n.getValue());  
        depthFirst(n.getLeft());  
        depthFirst(n.getRight());  
    }  
}
```

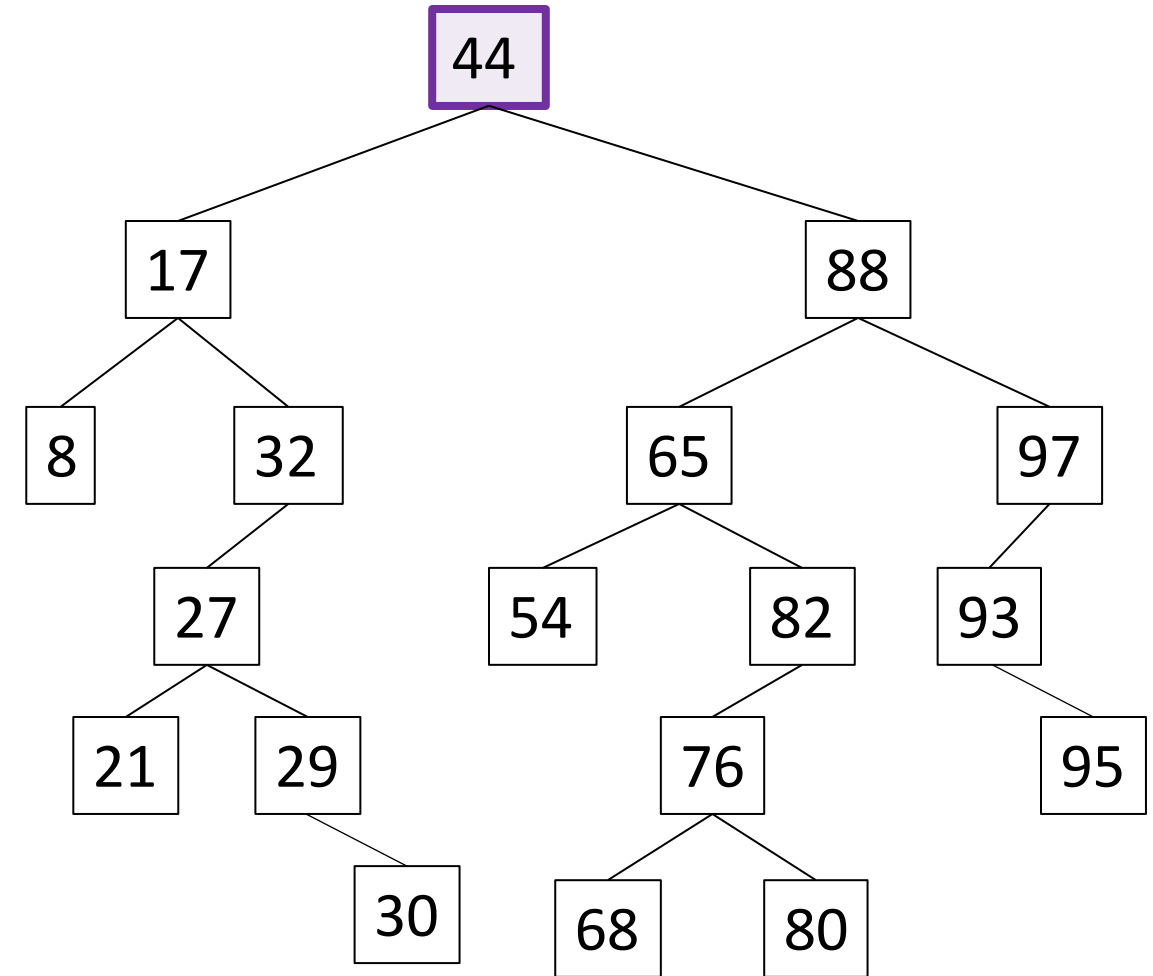
Recursion:

- Calling a method from inside itself.
- Solve the problem by solving identical smaller problems.
- What is the “smaller problem”?
 - Process the left side, then process the right side.



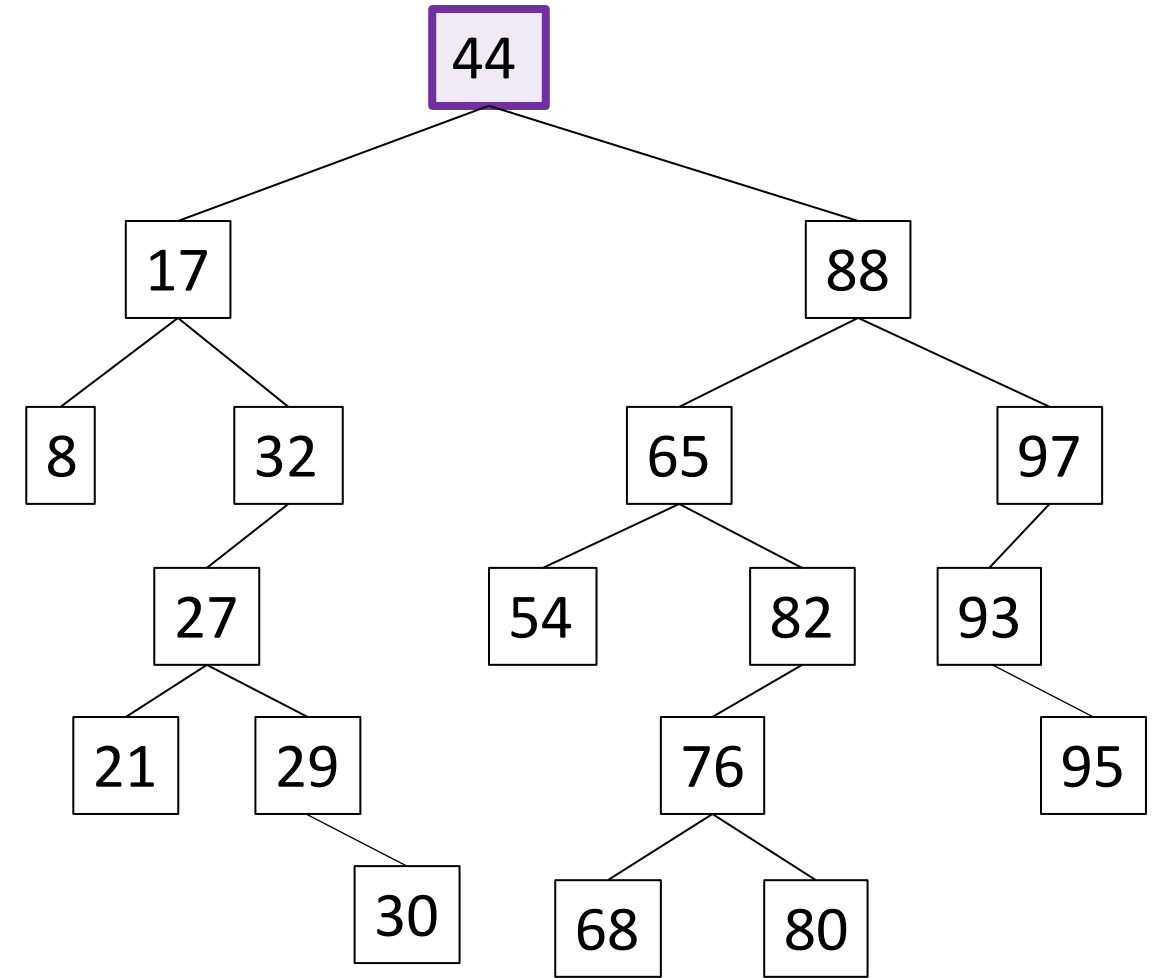
Binary Search Tree - Traversal

```
public void depthFirst(44) {  
    if (n != null) {  
        System.out.println(n.getValue());  
        depthFirst(n.getLeft());  
        depthFirst(n.getRight());  
    }  
}
```



Binary Search Tree - Traversal

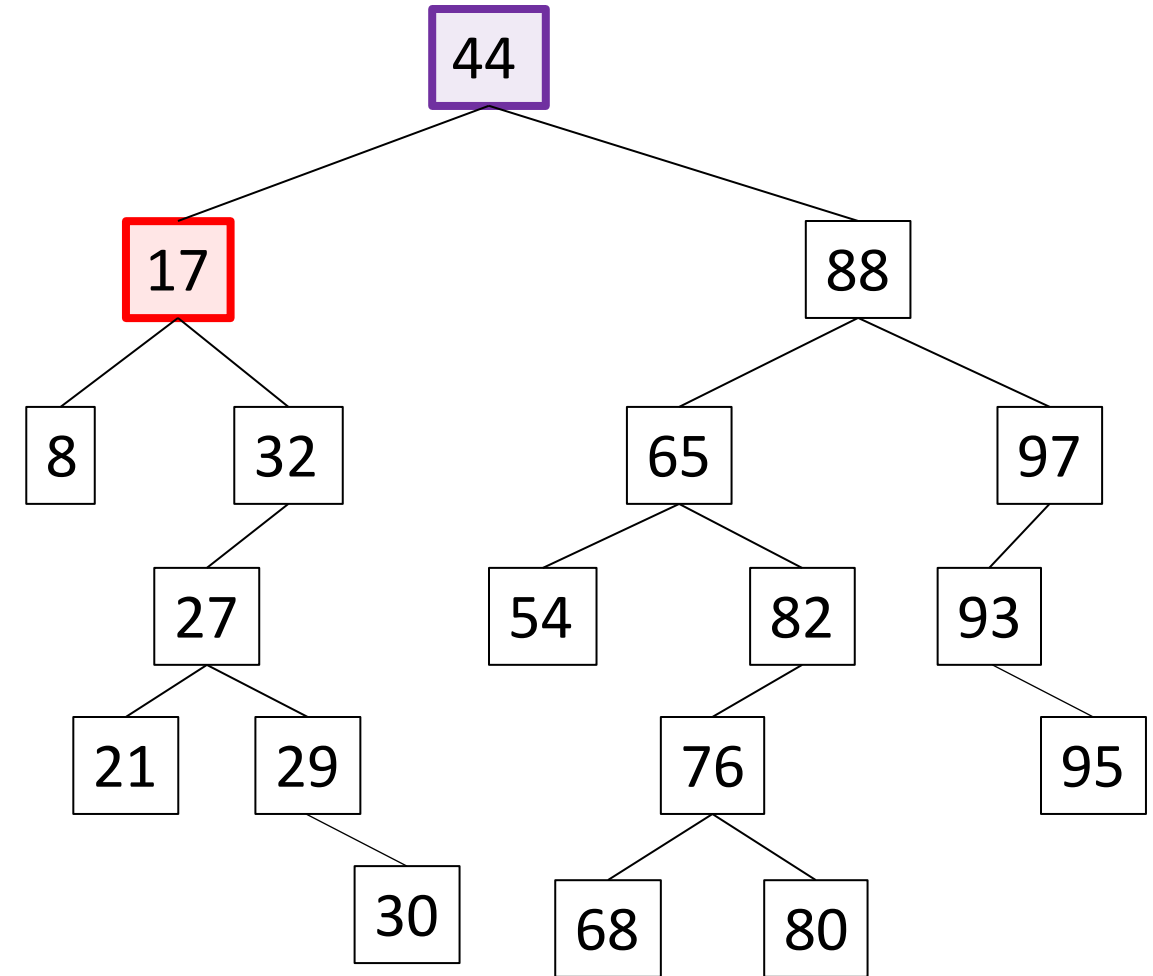
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Binary Search Tree - Traversal

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}
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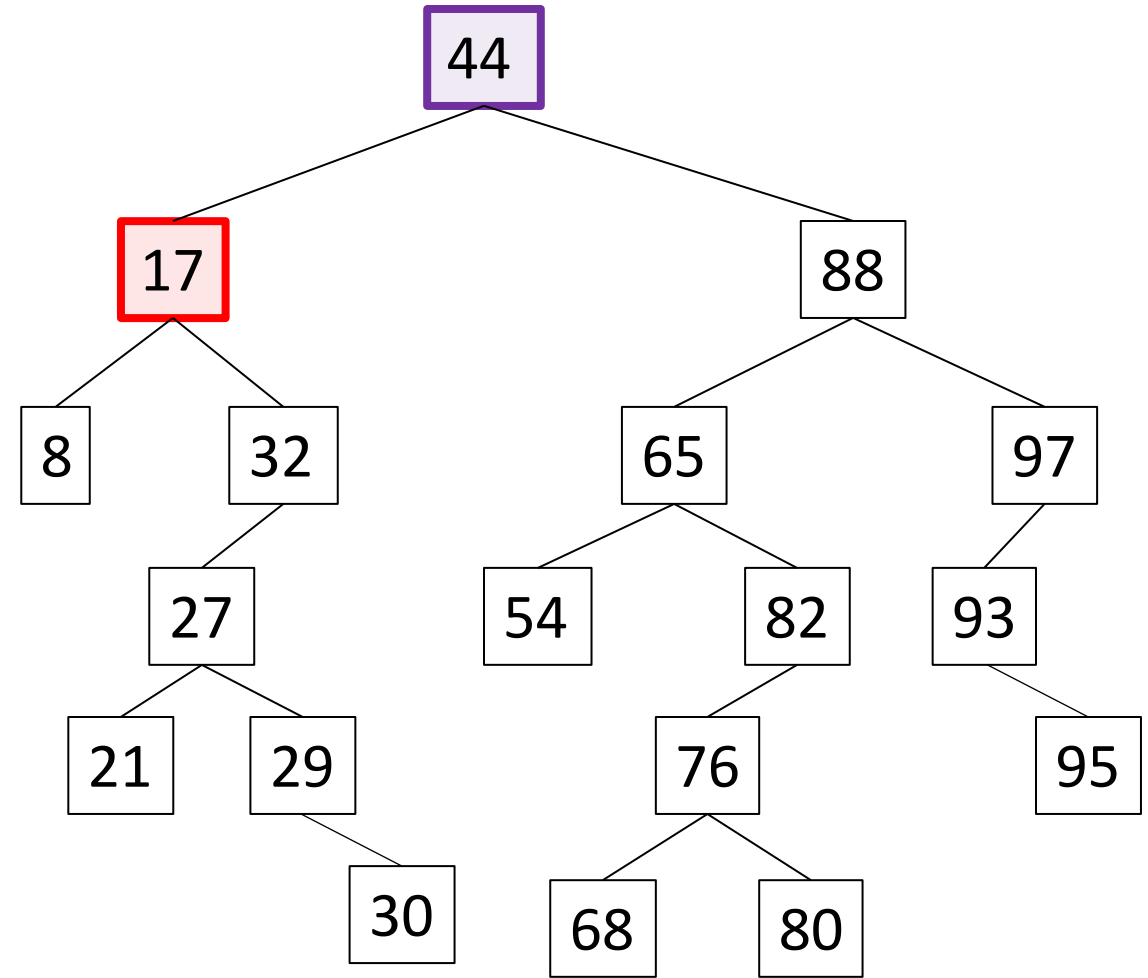
```
public void depthFirst(17) {  
    if (n != null) {  
        System.out.println(n.getValue());  
        depthFirst(n.getLeft());  
        depthFirst(n.getRight());  
    }  
}
```



Binary Search Tree - Traversal

```
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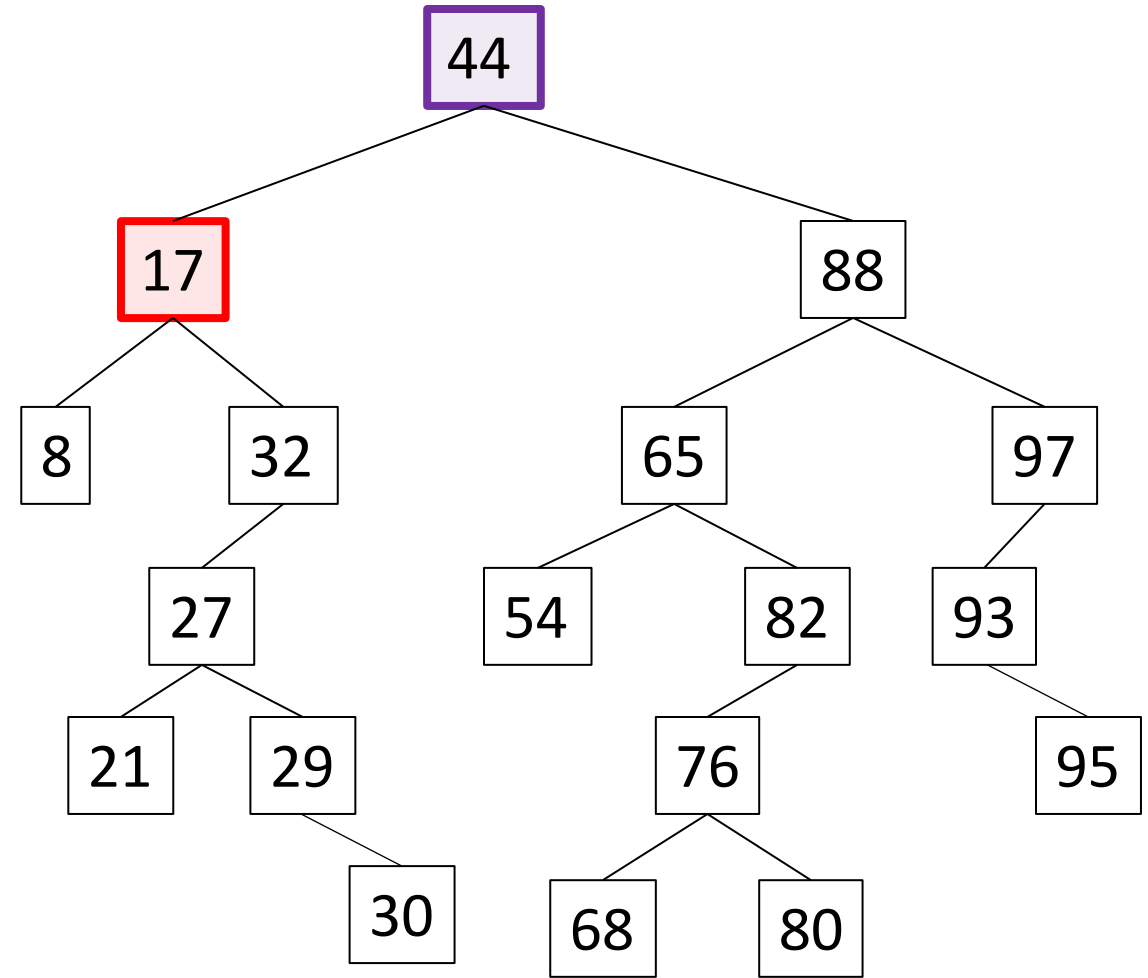
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Binary Search Tree - Traversal

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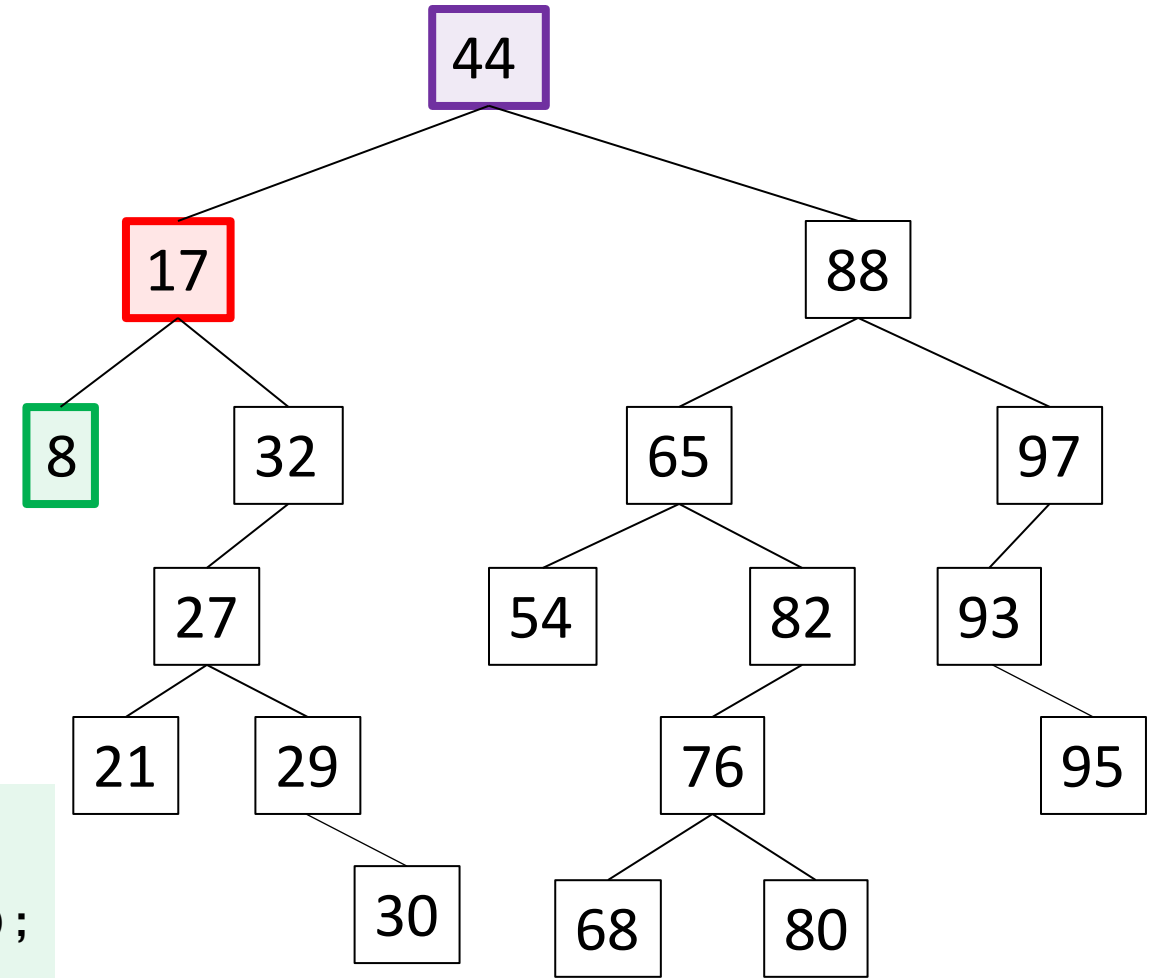


Binary Search Tree - Traversal

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public void depthFirst(44) {  
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    if (n != null) {  
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        depthFirst(n.getLeft());  
        depthFirst(n.getRight());  
    }  
}
```

```
public void depthFirst(8) {  
    if (n != null) {  
        System.out.println(n.getValue());  
        depthFirst(n.getLeft());  
        depthFirst(n.getRight());  
    }  
}
```

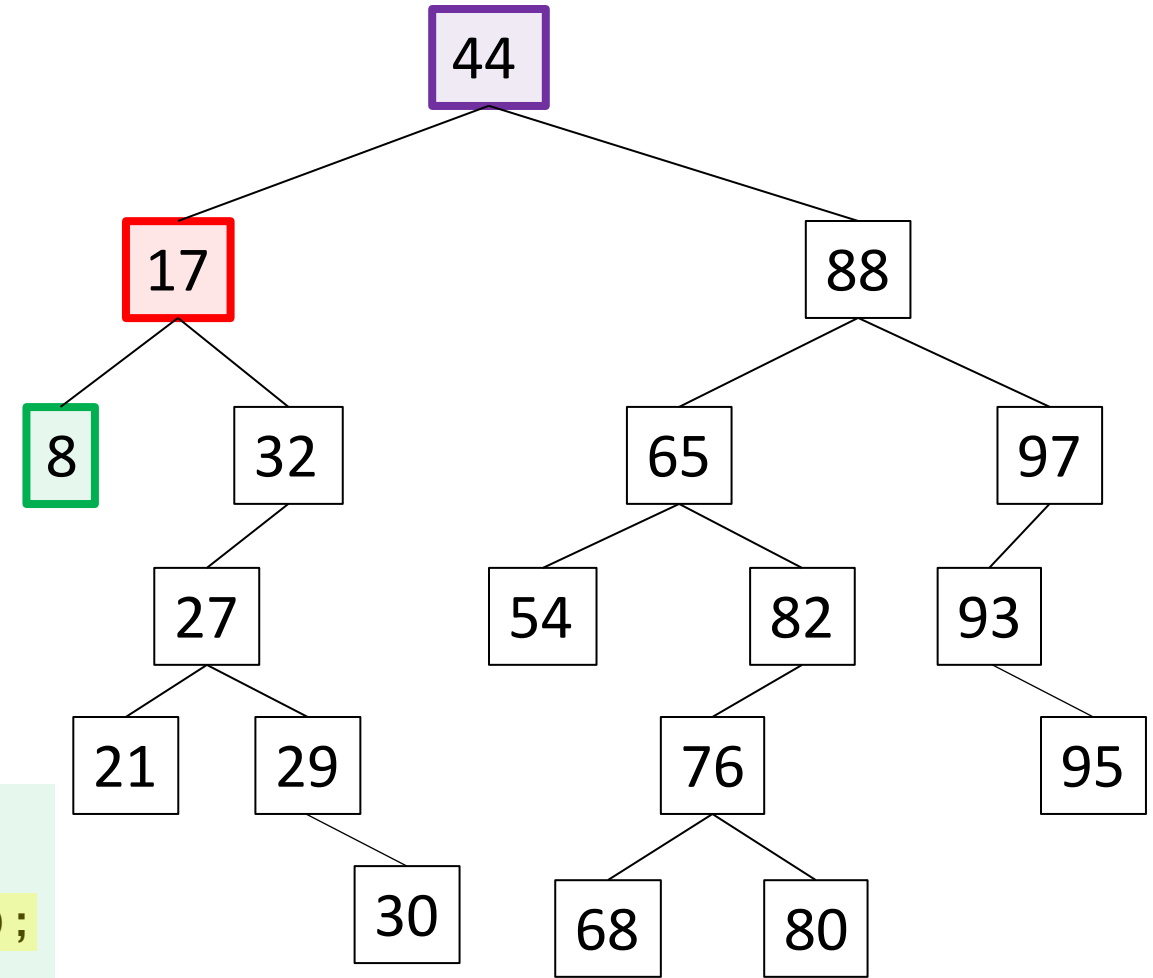


Binary Search Tree - Traversal

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public void depthFirst(44) {  
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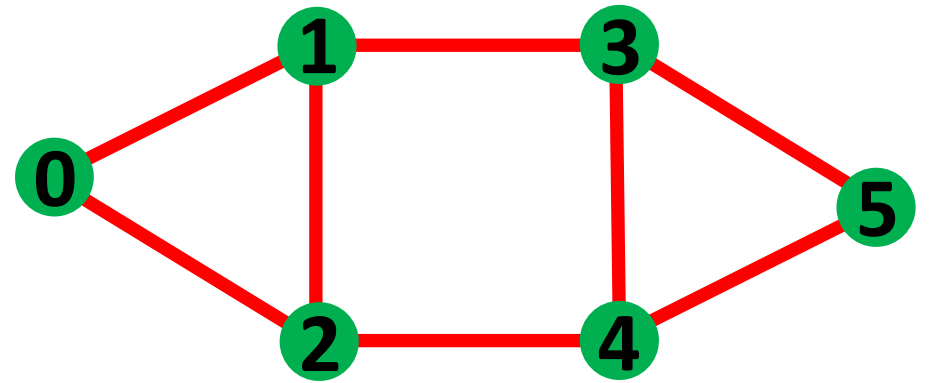
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```
public void depthFirst(8) {  
    if (n != null) {  
        System.out.println(n.getValue());  
        depthFirst(n.getLeft());  
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    }  
}
```



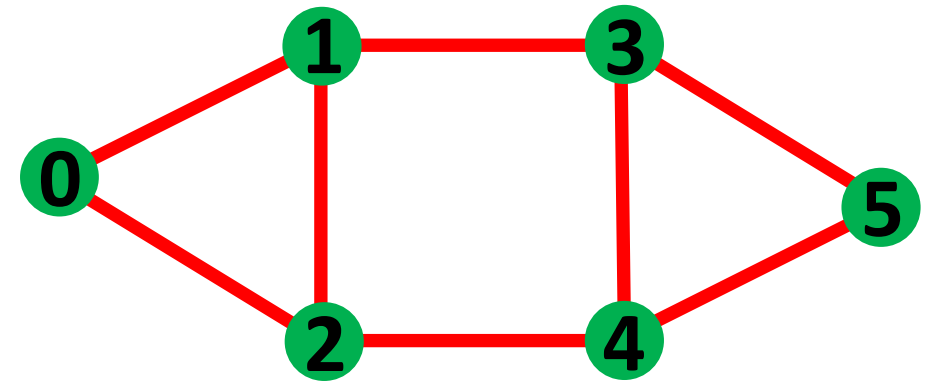
Graphs - Traversal

```
public void depthFirst(Node n) {  
    if (n != null) {  
        System.out.println(n.getValue());  
        depthFirst(n.getLeft());  
        depthFirst(n.getRight());  
    }  
}
```



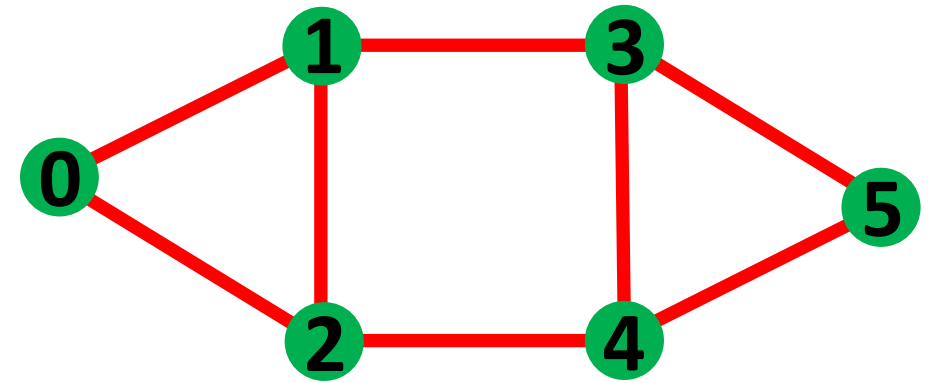
Graphs - Traversal

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Graphs - Traversal

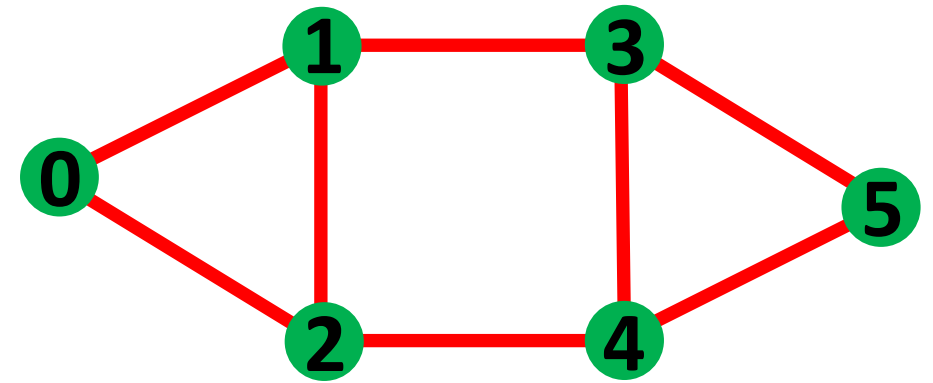
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    }  
}
```



Graphs - Traversal

int

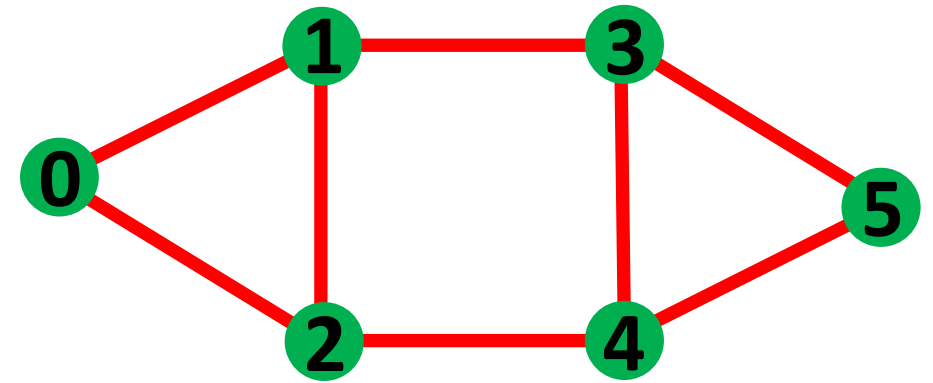
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Graphs - Traversal

int

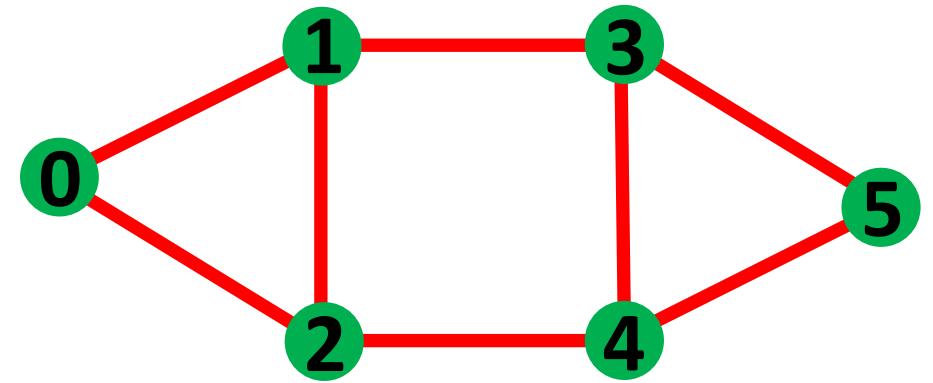
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Graphs - Traversal

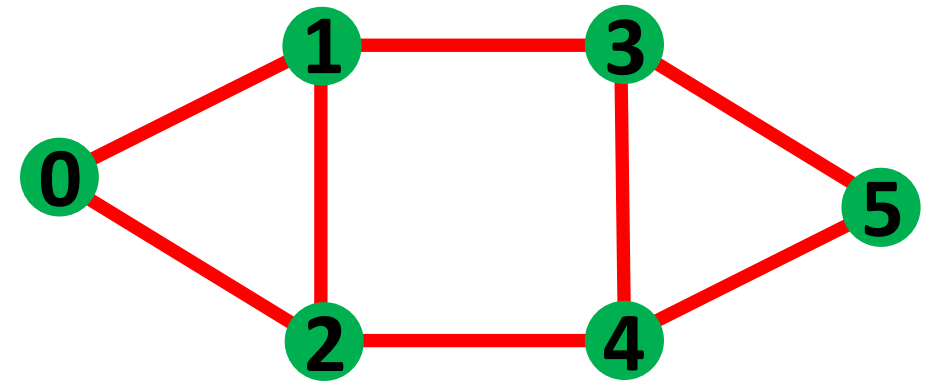
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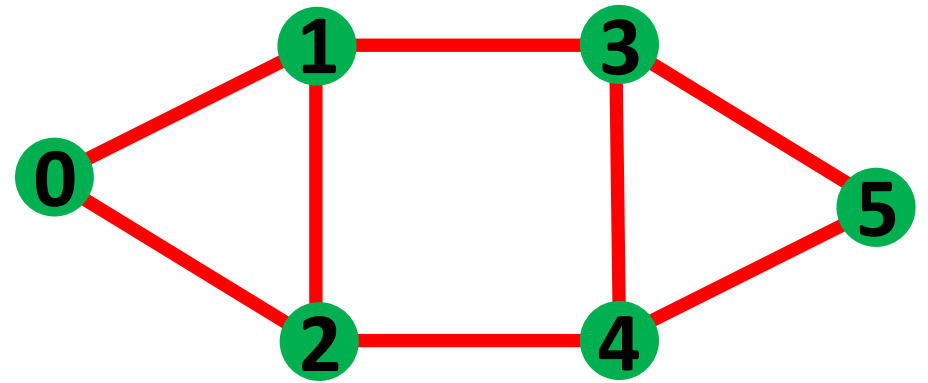
Graphs - Traversal

```
public void depthFirst(Node int n) {  
    if (n != null) {  
        System.out.println(n.getValue());  
        depthFirst(n.getLeft());  
        depthFirst(n.getRight());  
    }  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```



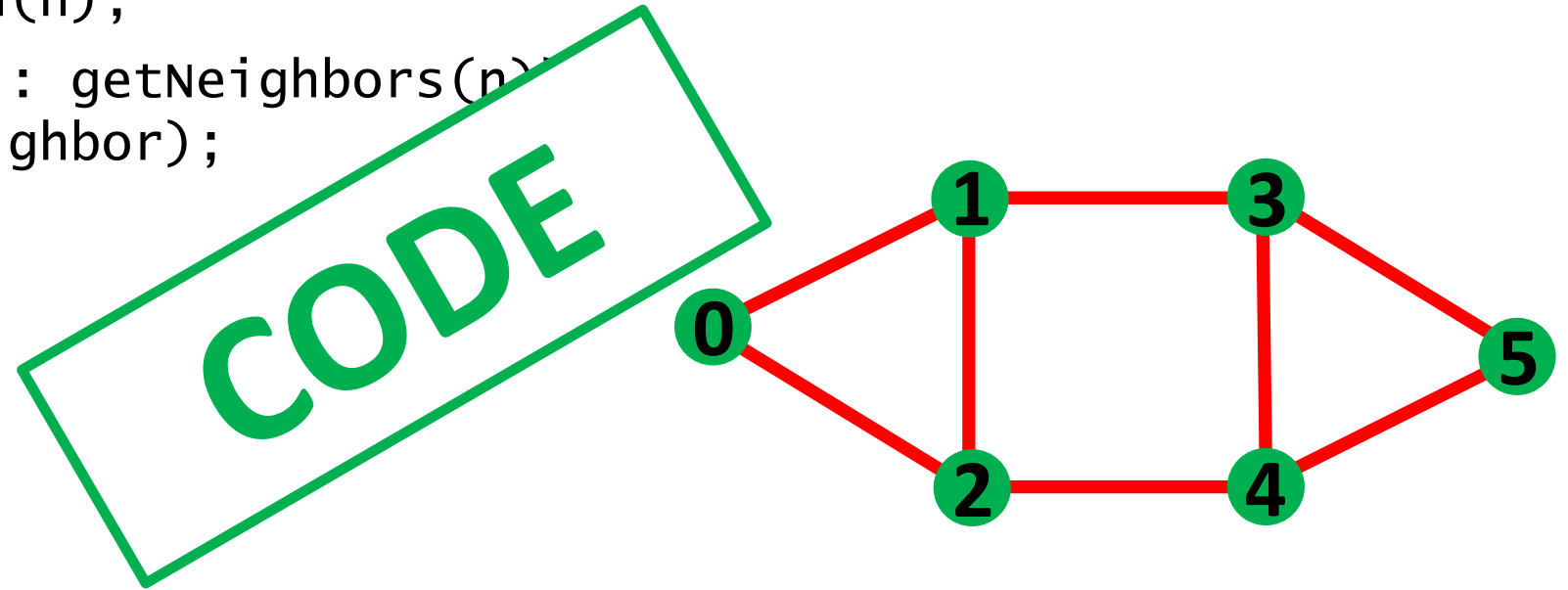
Graphs - Traversal

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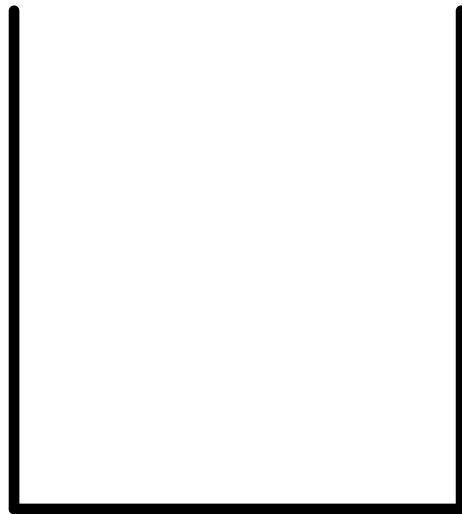
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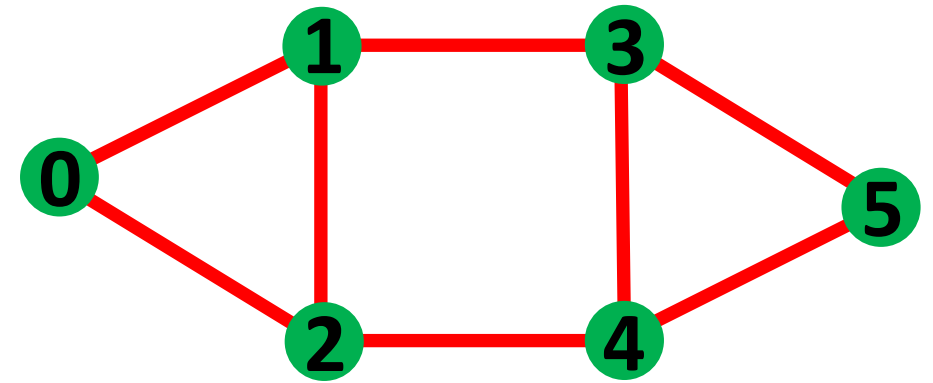
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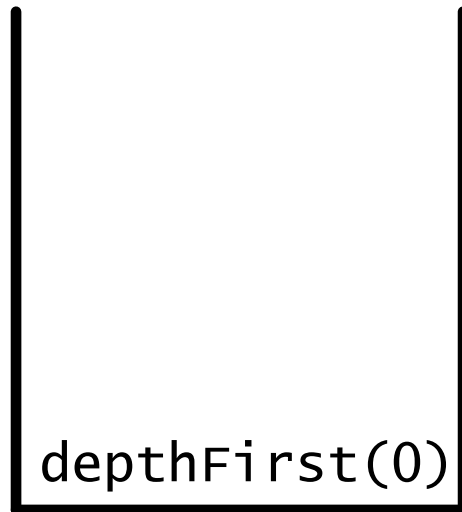
Run-time Stack

Output



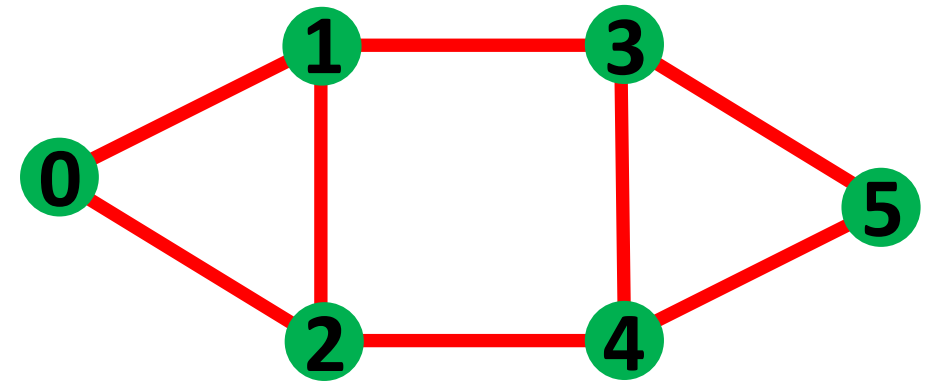
Graphs - Traversal

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public void depthFirst(int n) {  
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    }  
}
```



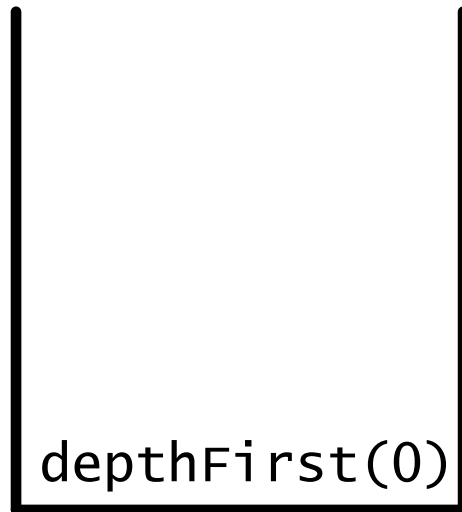
Run-time Stack

Output

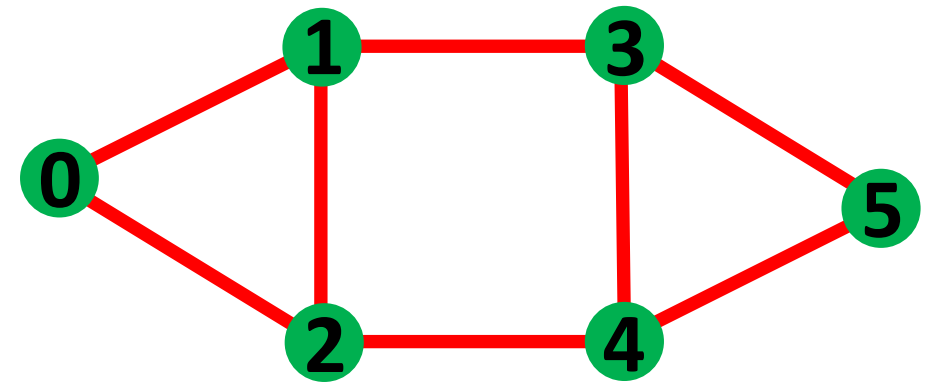
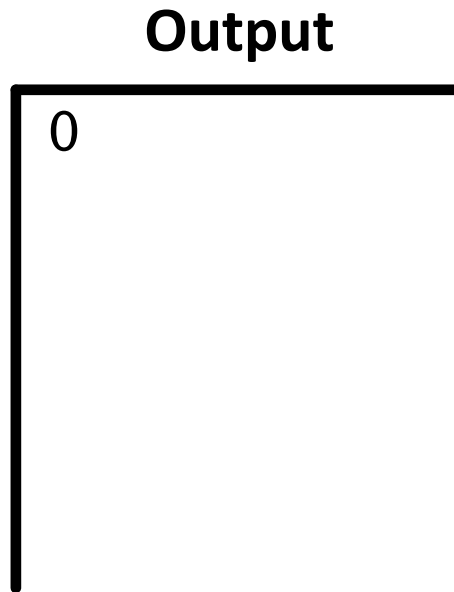


Graphs - Traversal

```
public void depthFirst(int n) {  
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    }  
}
```

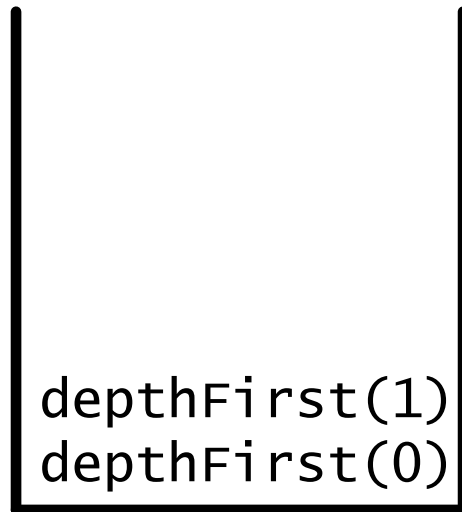


Run-time Stack



Graphs - Traversal

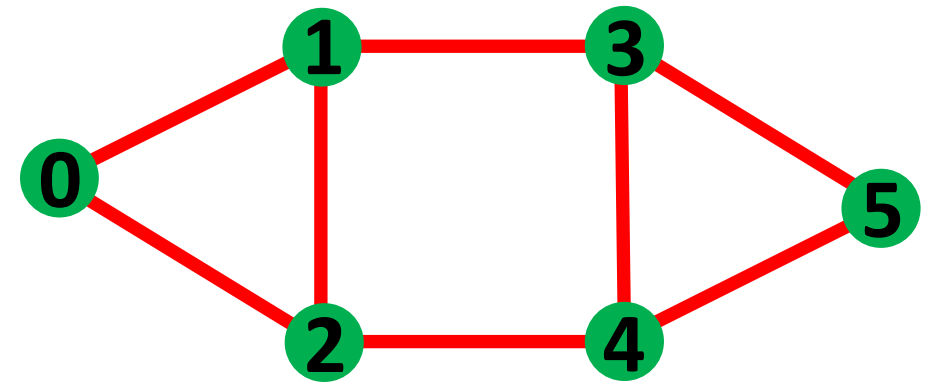
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    }  
}
```



Run-time Stack

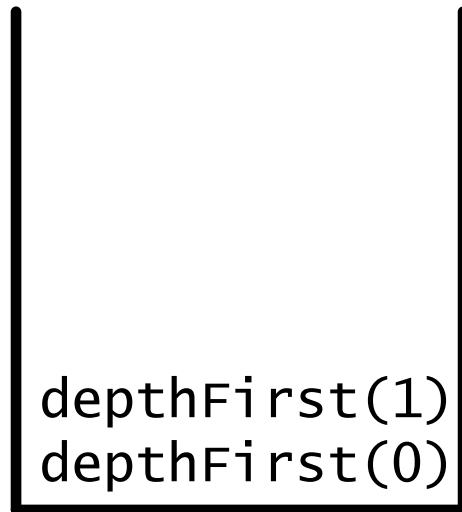
Output

0



Graphs - Traversal

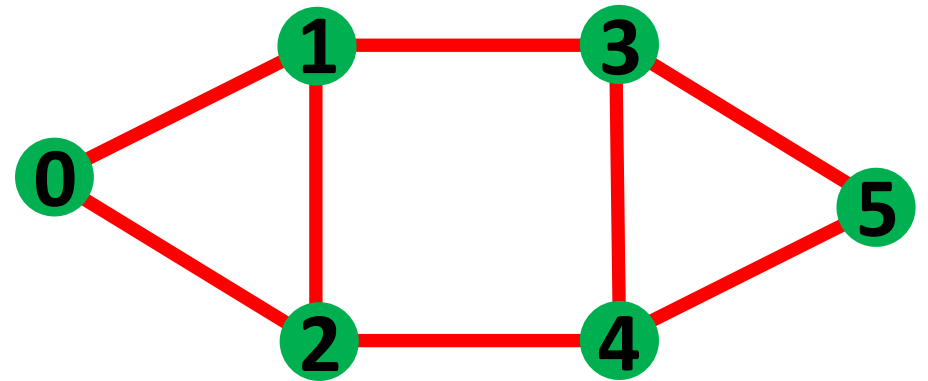
```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```



Run-time Stack

Output

0
1



Graphs - Traversal

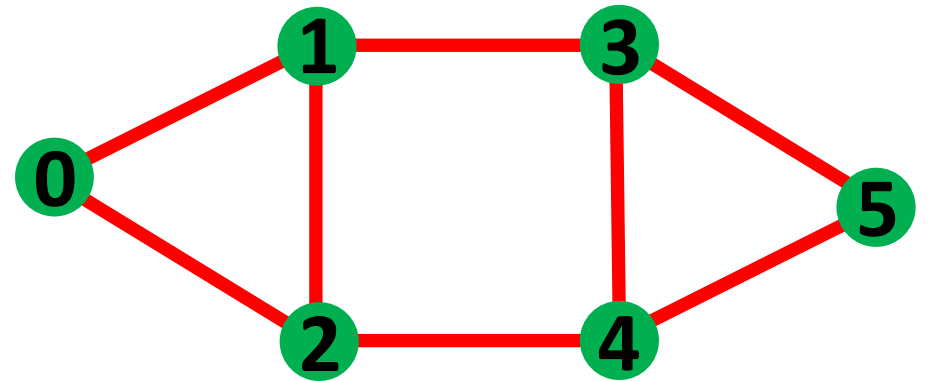
```
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    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```

depthFirst(0)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1



Graphs - Traversal

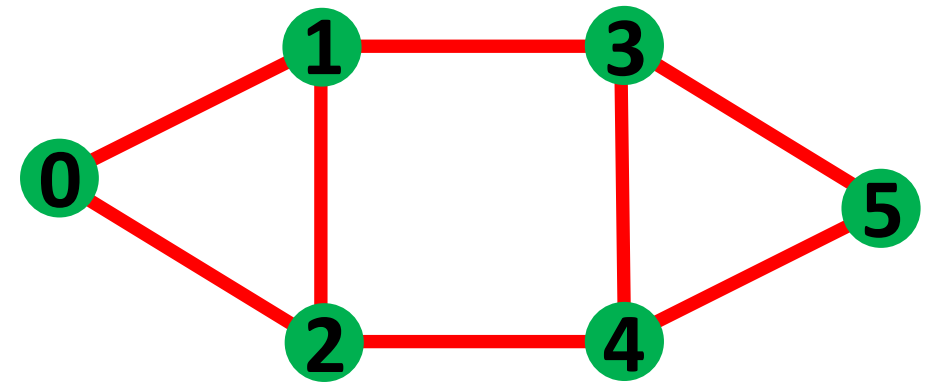
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depthFirst(0)
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depthFirst(0)

Run-time Stack

Output

0
1
0



Graphs - Traversal

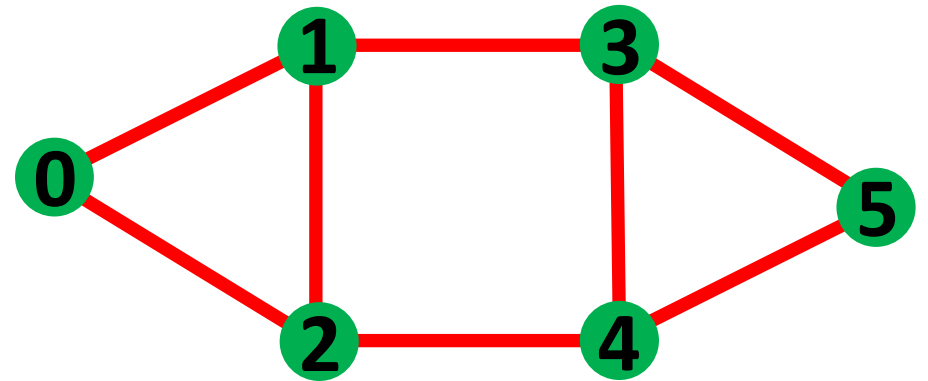
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    }  
}
```

depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
0



Graphs - Traversal

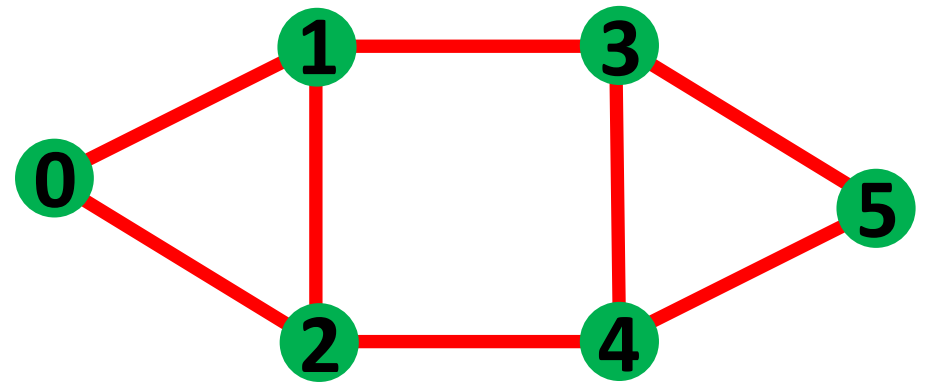
```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```

depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
0
1



Graphs - Traversal

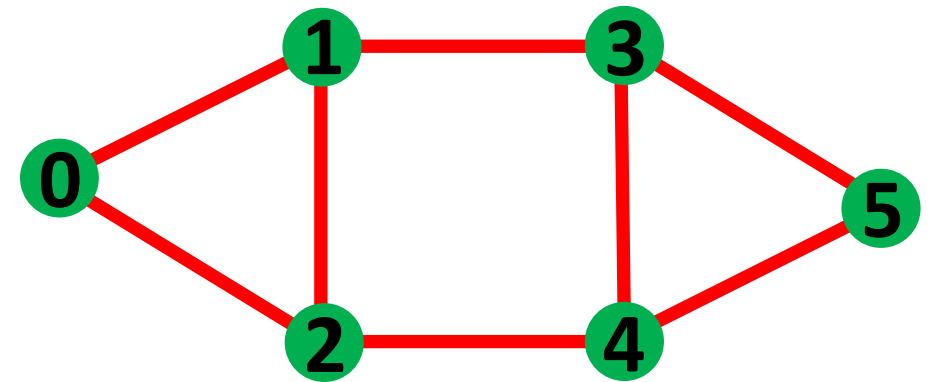
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    }  
}
```

depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
0
1
0



Graphs - Traversal

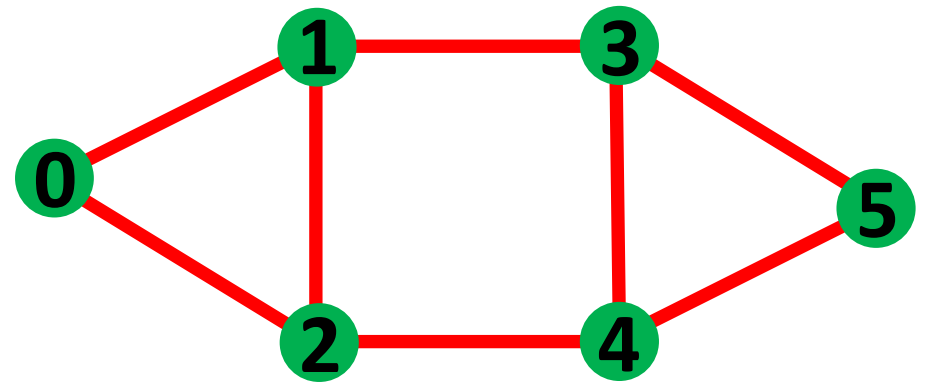
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        depthFirst(neighbor);  
    }  
}
```

depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
0
1
0
1



Graphs - Traversal

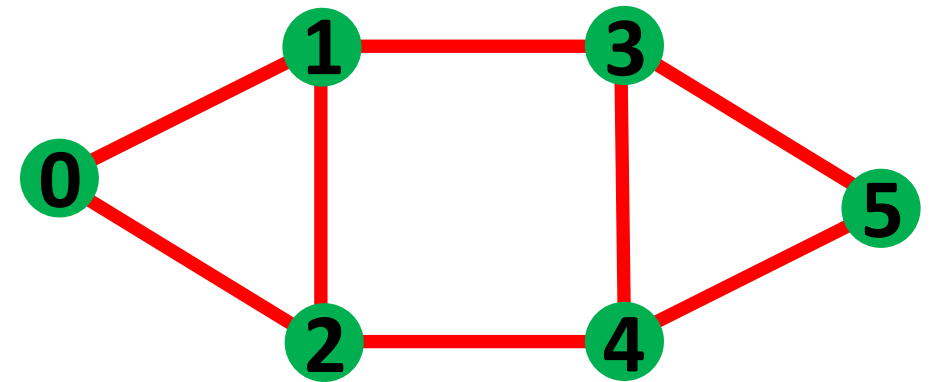
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    }  
}
```

```
depthFirst(0)  
depthFirst(1)  
depthFirst(0)  
depthFirst(1)  
depthFirst(0)  
depthFirst(1)  
depthFirst(0)
```

Run-time Stack

Output

```
0  
1  
0  
1  
0  
1  
0
```



Graphs - Traversal

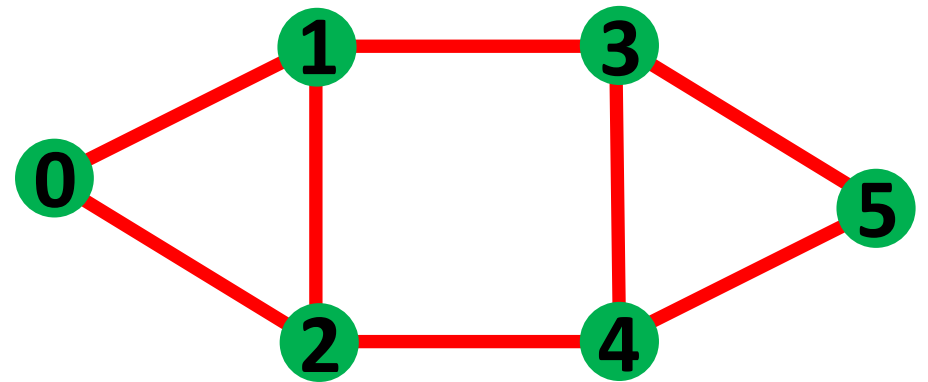
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    }  
}
```

```
depthFirst(1)  
depthFirst(0)  
depthFirst(1)  
depthFirst(0)  
depthFirst(1)  
depthFirst(0)  
depthFirst(1)  
depthFirst(0)
```

Run-time Stack

Output

```
0  
1  
0  
1  
0  
1  
0  
1
```



Graphs - Traversal

```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```

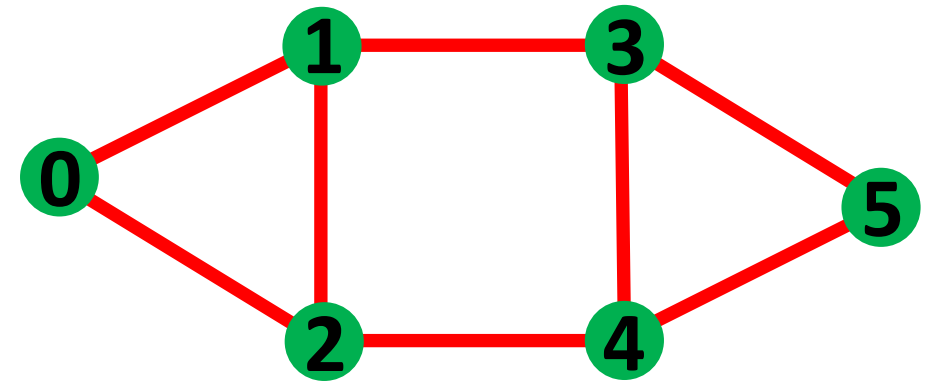
}

depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output



0
1
0
1
0
1
0
1
0
1
0



Graphs - Traversal

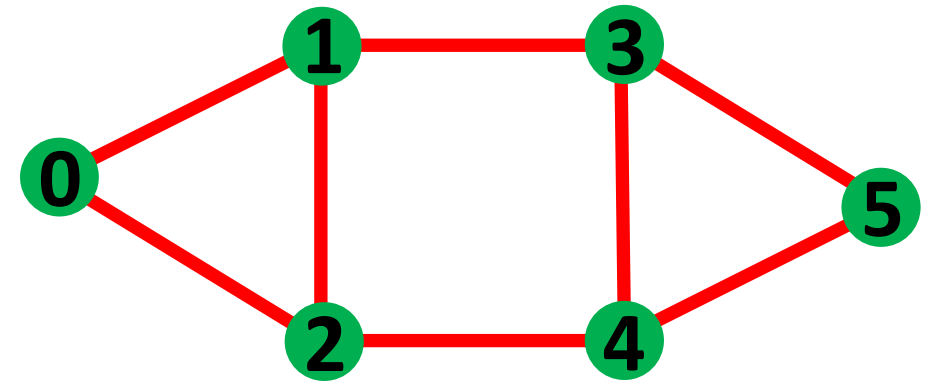
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}
```

**STACK OVERFLOW
ERROR**



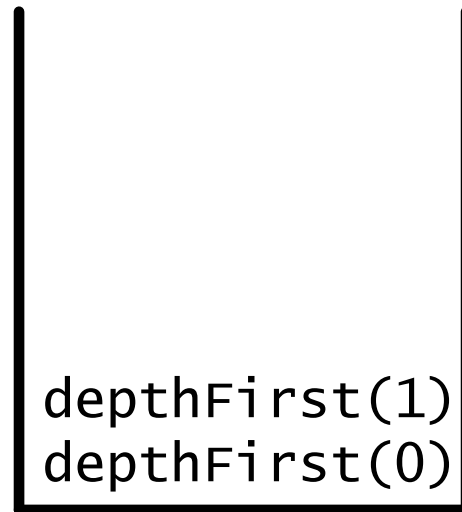
depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)
depthFirst(1)
depthFirst(0)

Run-time Stack



Graphs - Traversal

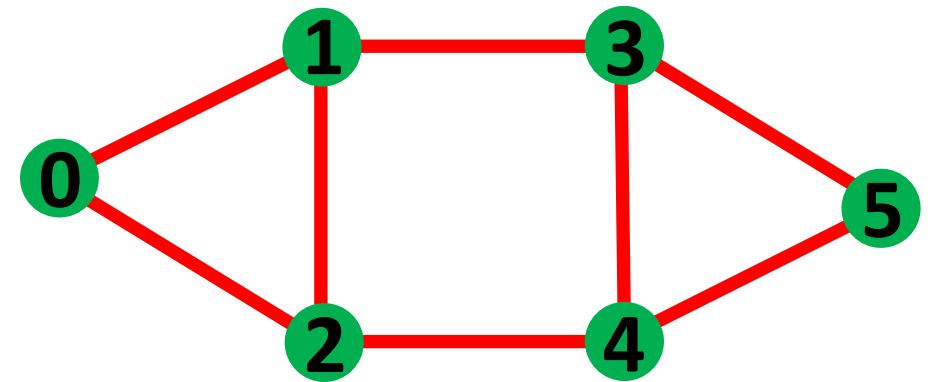
```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```



Run-time Stack

Output

0
1

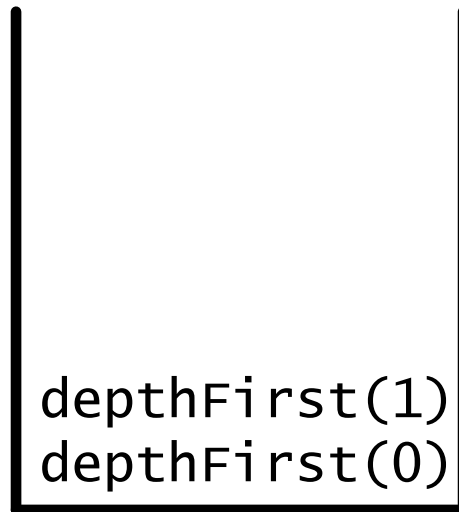


Where is the problem?

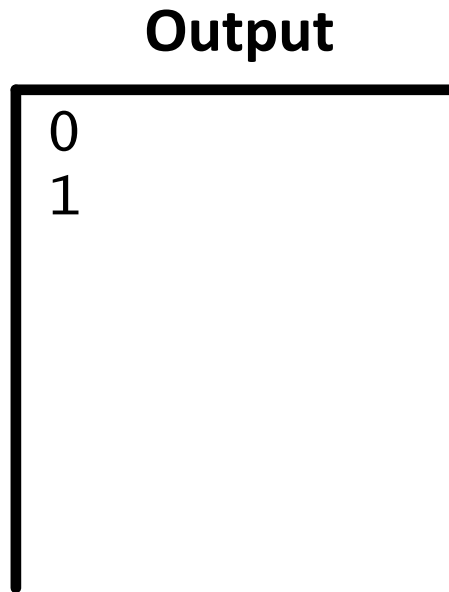
Graphs - Traversal

What neighbors should we call `depthFirst()` on?

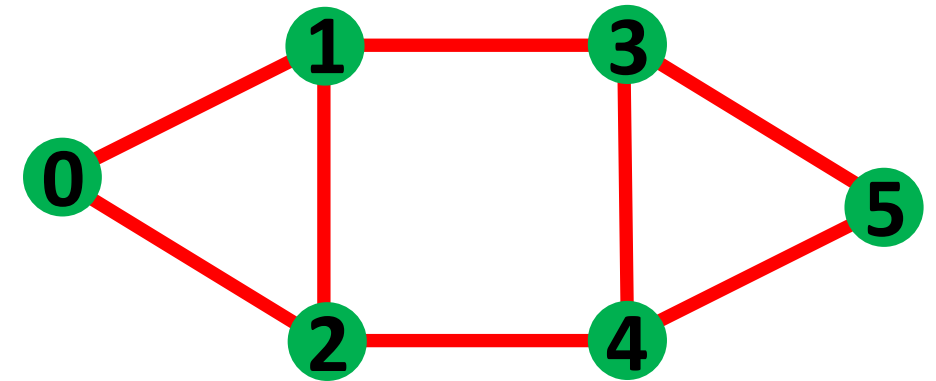
```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```



Run-time Stack



Output

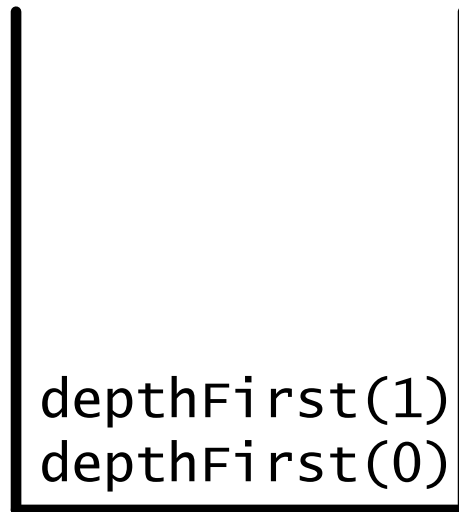


Graphs - Traversal

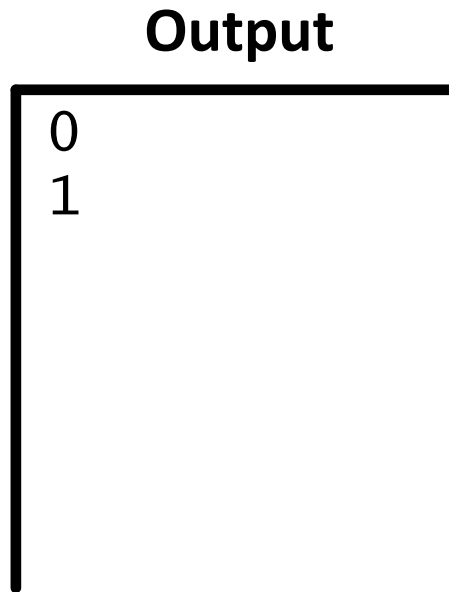
```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```

What neighbors should we call `depthFirst()` on?

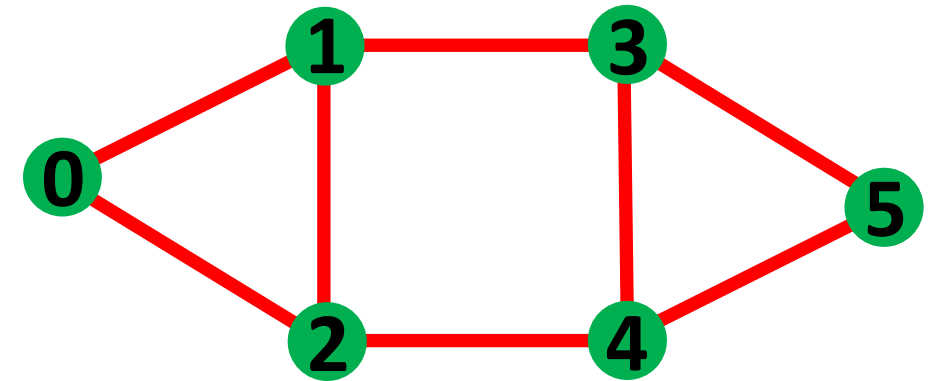
Neighbors that have not already been visited.



Run-time Stack

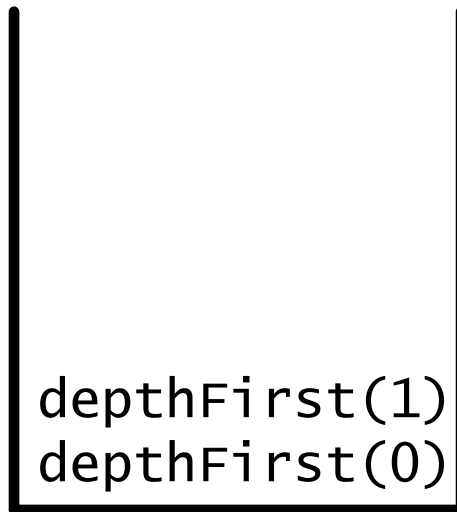


Output



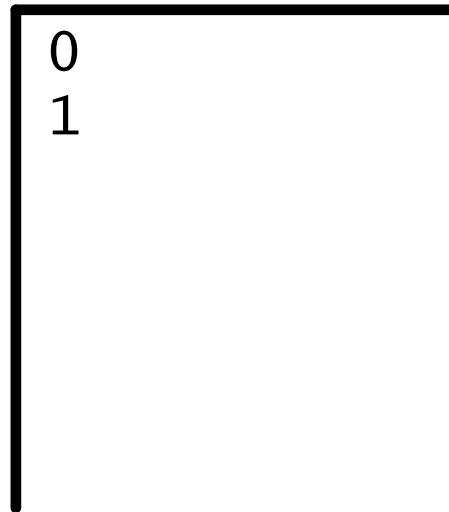
Graphs - Traversal

```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```



Run-time Stack

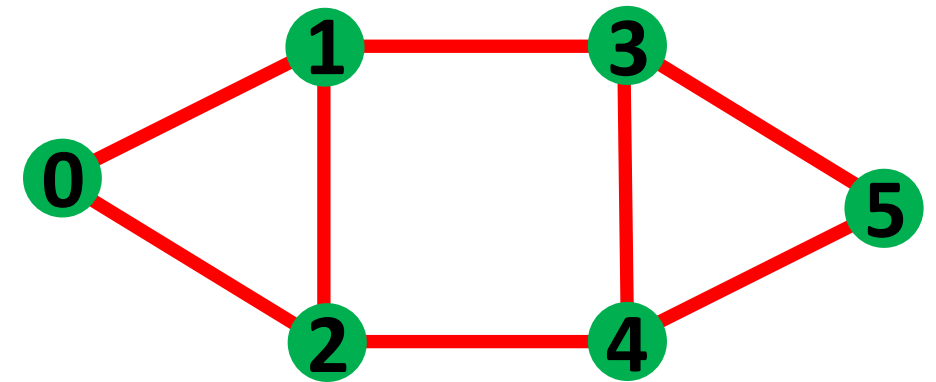
Output



What neighbors should we call `depthFirst()` on?

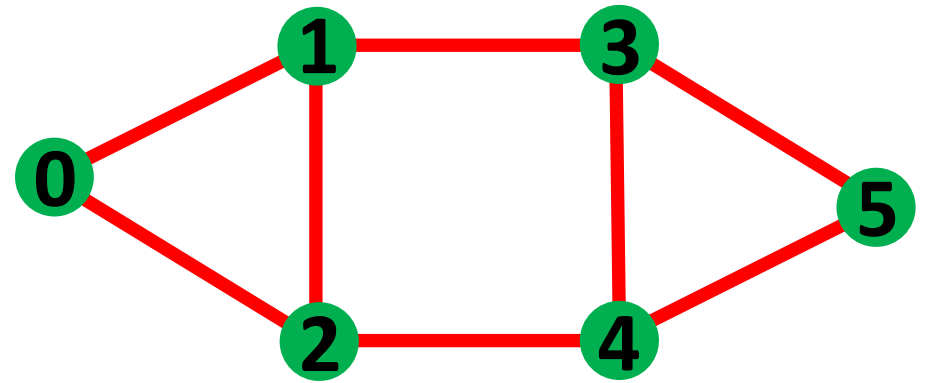
Neighbors that have not already been visited.

How can we do that?



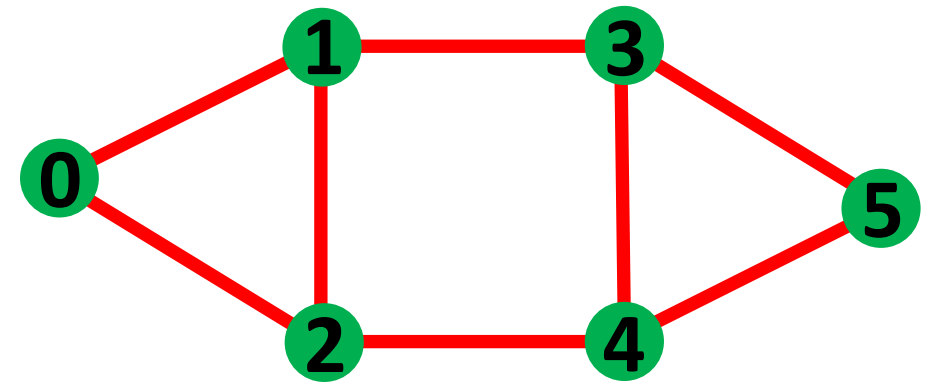
Graphs - Traversal

```
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```



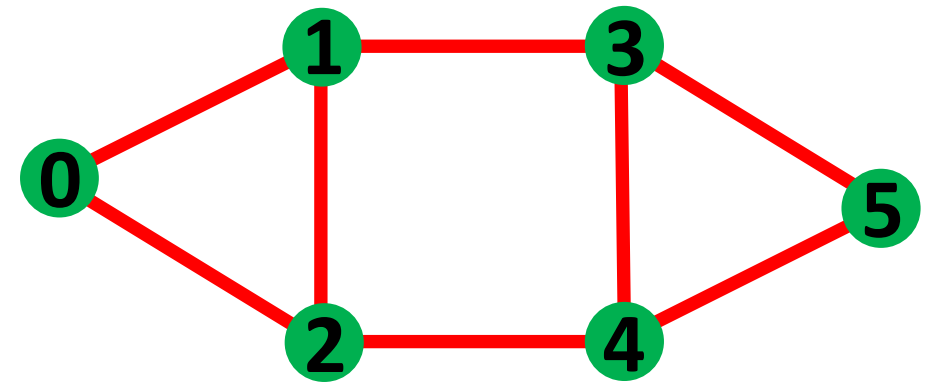
Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        depthFirst(neighbor);  
    }  
}
```



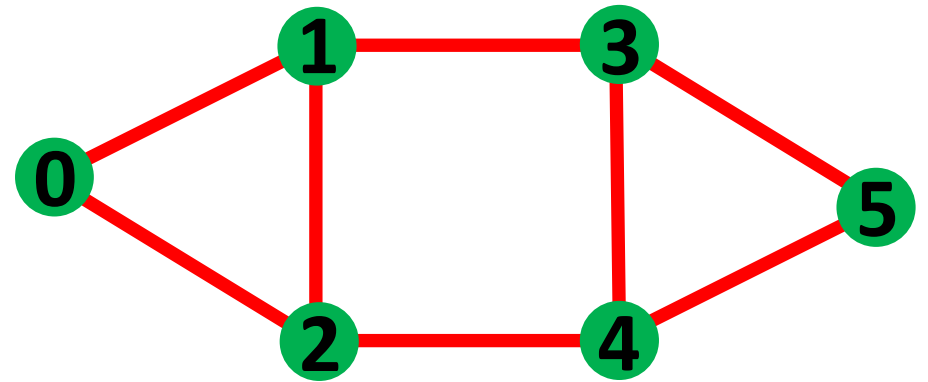
Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



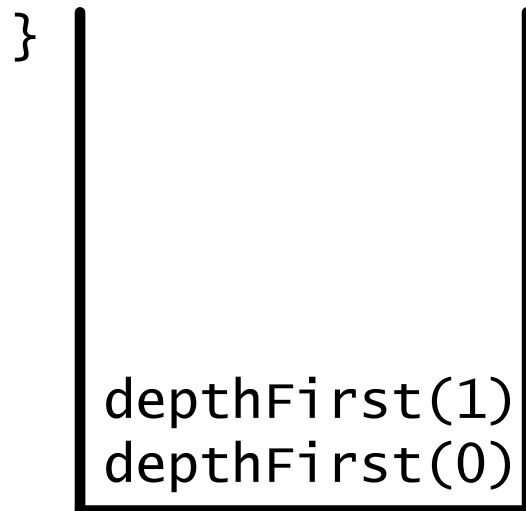
Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Graphs - Traversal

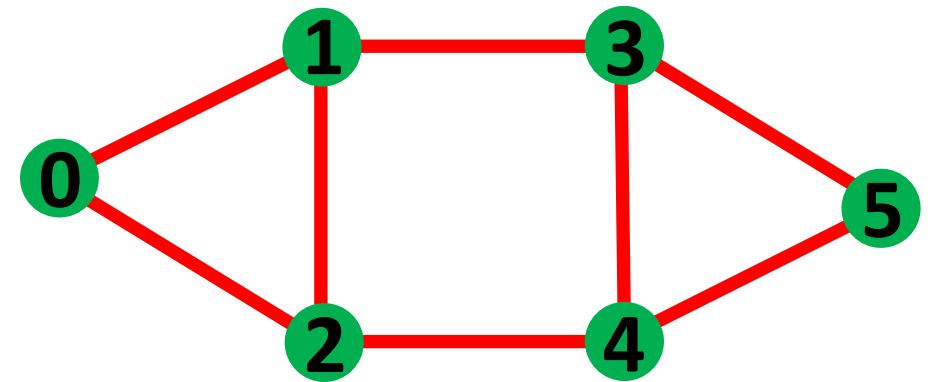
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Run-time Stack

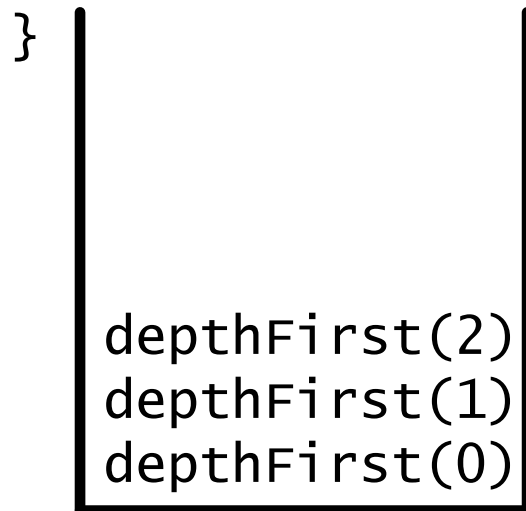
Output

0
1



Graphs - Traversal

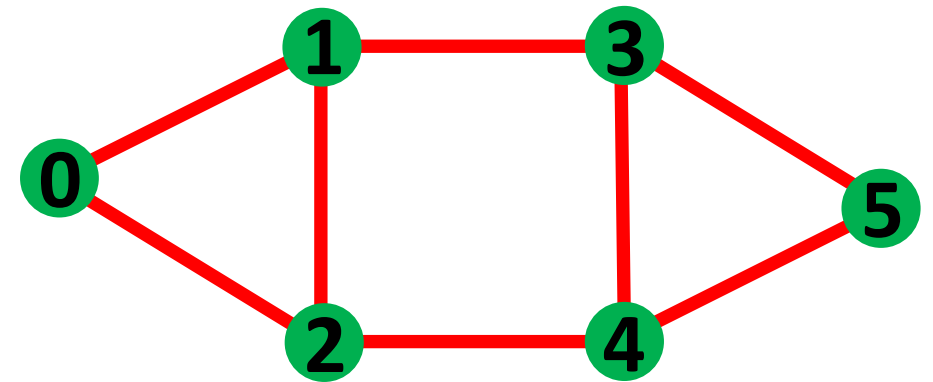
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Run-time Stack

Output

0
1



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

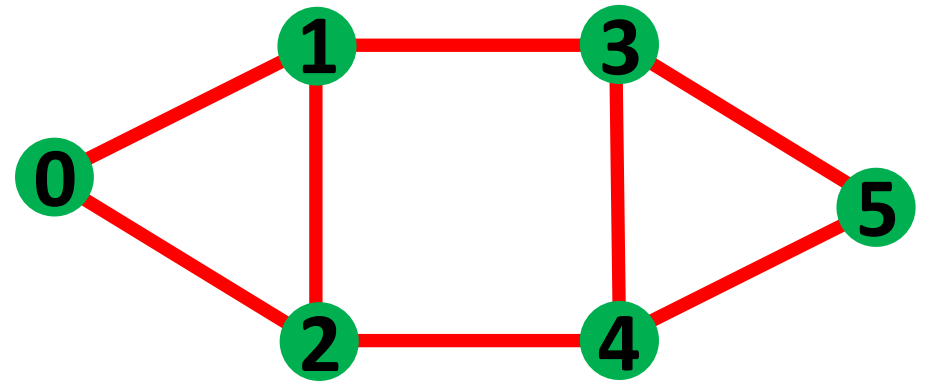
}

depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

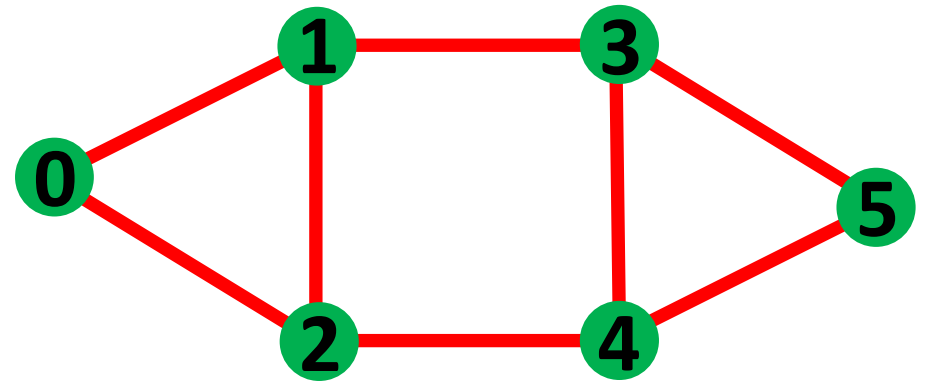
}

depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

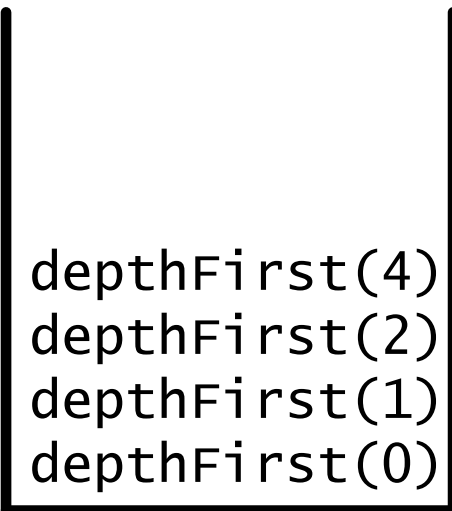
0
1
2



Graphs - Traversal

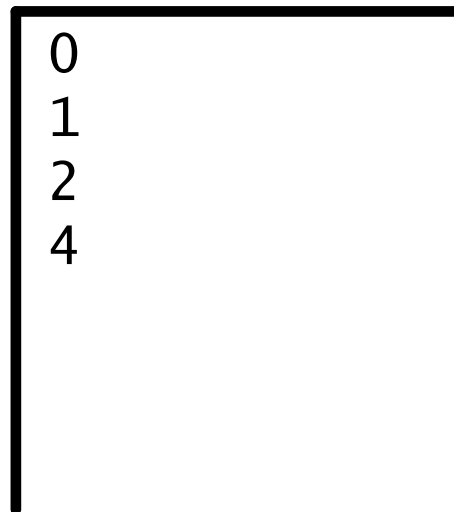
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

Run-time Stack

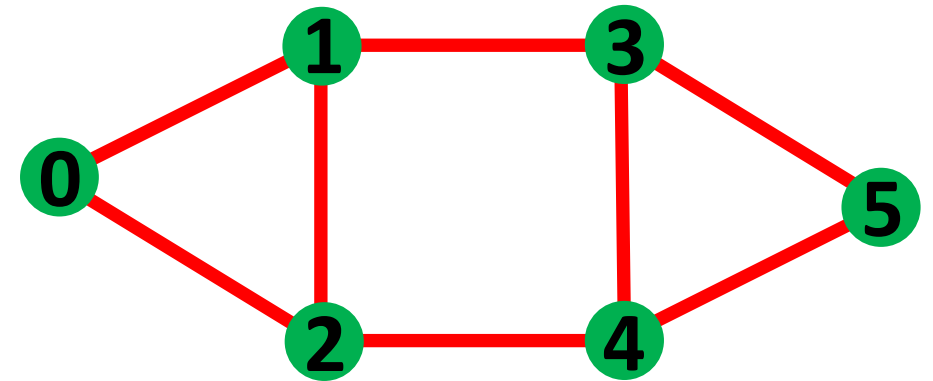
A vertical rectangle representing a stack. Inside, from bottom to top, are the labels: depthFirst(0), depthFirst(1), depthFirst(2), and depthFirst(4).

```
depthFirst(4)  
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Output

A vertical rectangle representing an output stream. Inside, from top to bottom, are the labels: 0, 1, 2, and 4.

```
0  
1  
2  
4
```



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

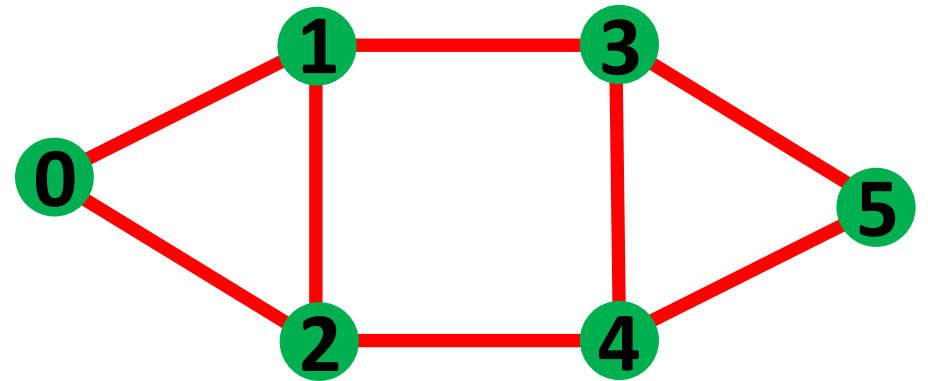
}

depthFirst(3)
depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4



Graphs - Traversal

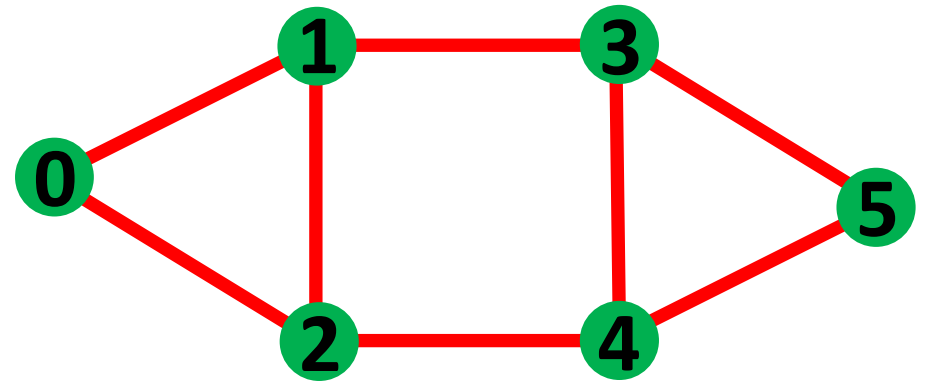
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

```
depthFirst(3)  
depthFirst(4)  
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Run-time Stack

Output

```
0  
1  
2  
4  
3
```



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

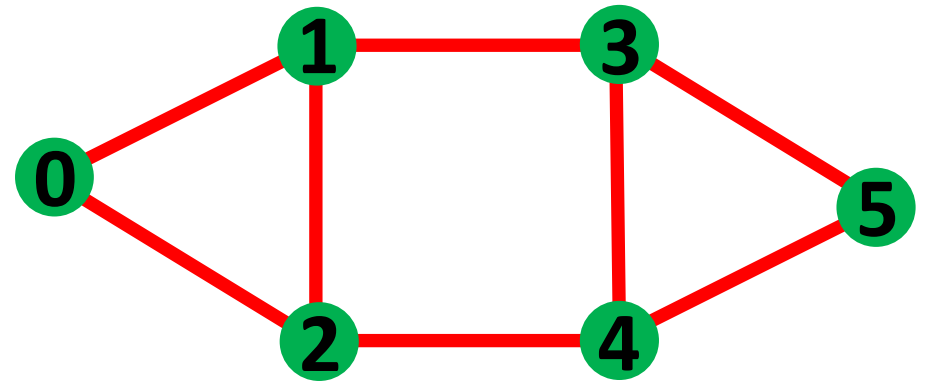
}

depthFirst(5)
depthFirst(3)
depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4
3



Graphs - Traversal

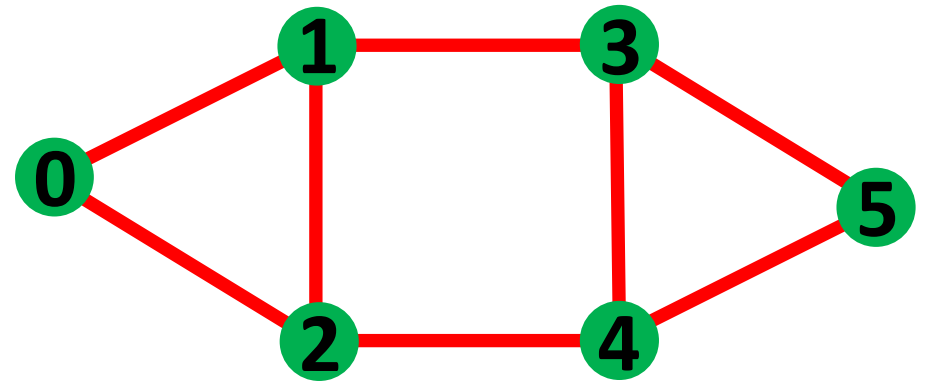
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

```
depthFirst(5)  
depthFirst(3)  
depthFirst(4)  
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Run-time Stack

Output

```
0  
1  
2  
4  
3  
5
```



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

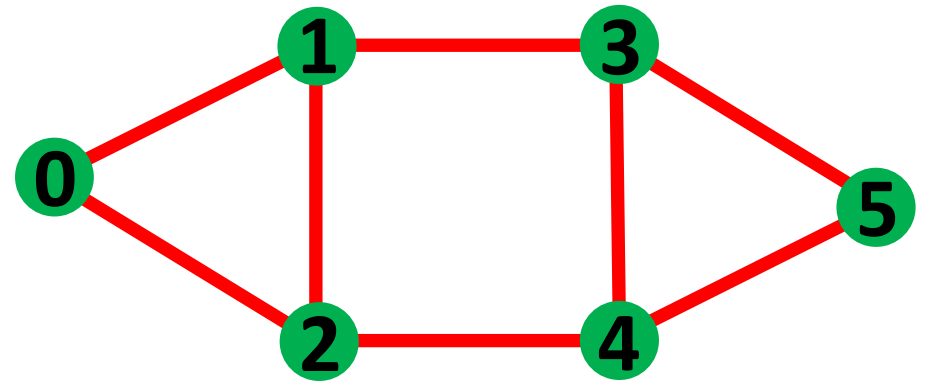
}

depthFirst(3)
depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4
3
5



Graphs - Traversal

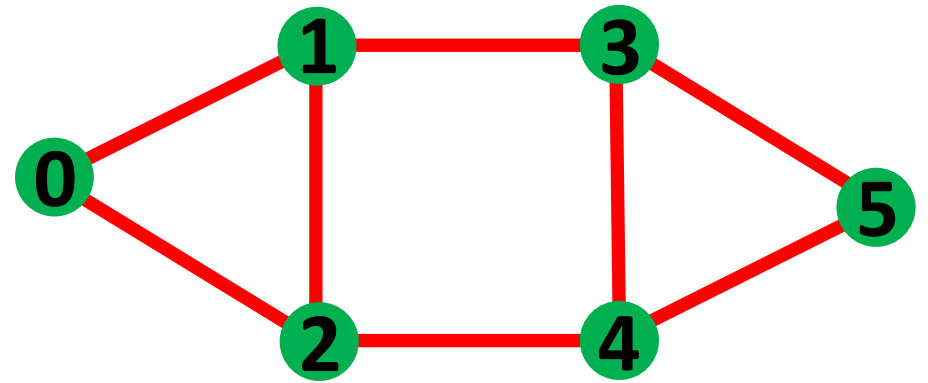
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

Run-time Stack

```
depthFirst(4)  
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Output

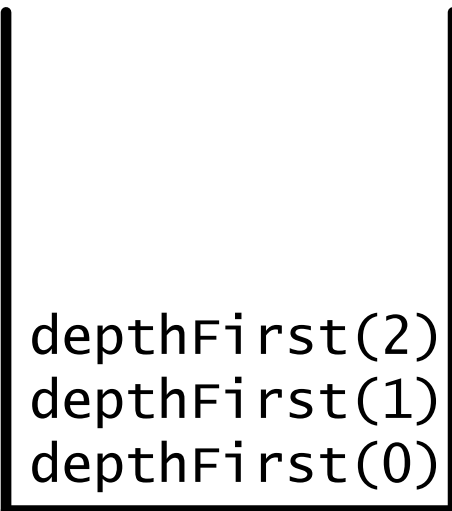
```
0  
1  
2  
4  
3  
5
```



Graphs - Traversal

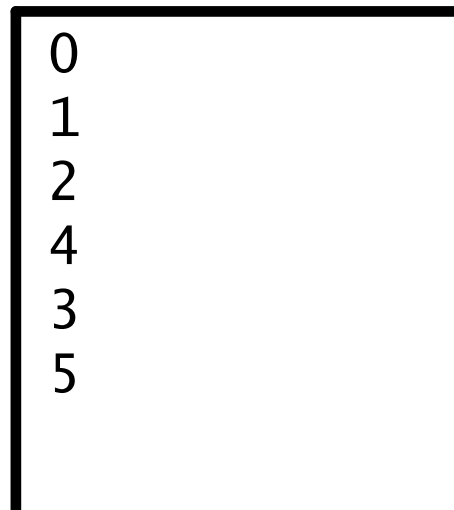
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

Run-time Stack

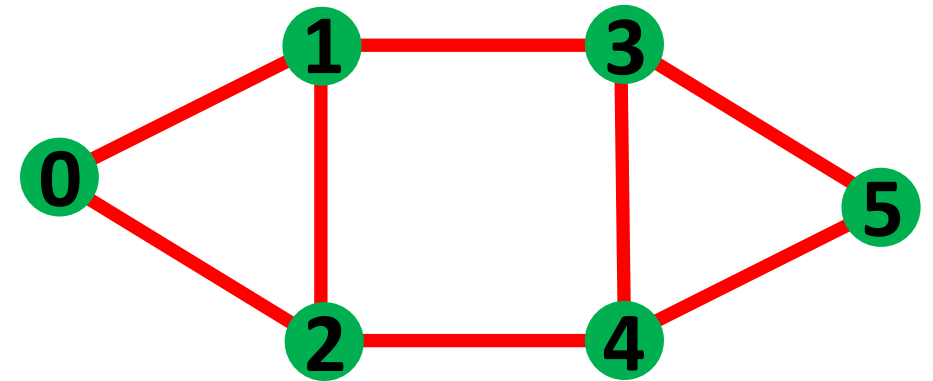
A diagram of a run-time stack represented as a vertical rectangle. Inside the rectangle, the following recursive calls are listed from bottom to top: depthFirst(0), depthFirst(1), and depthFirst(2).

```
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Output

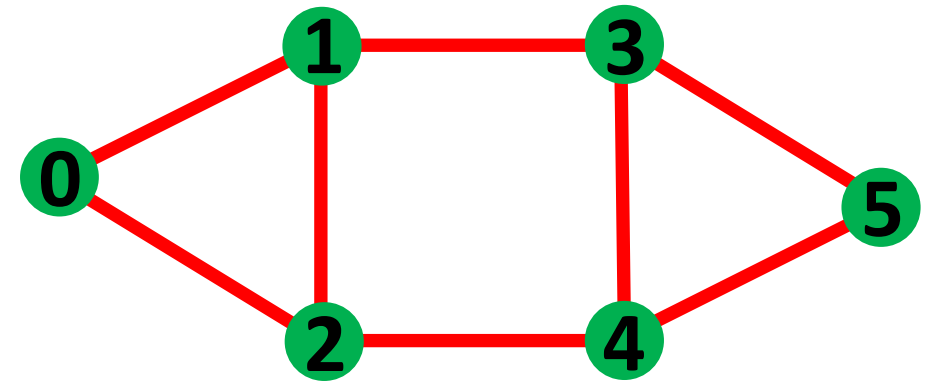
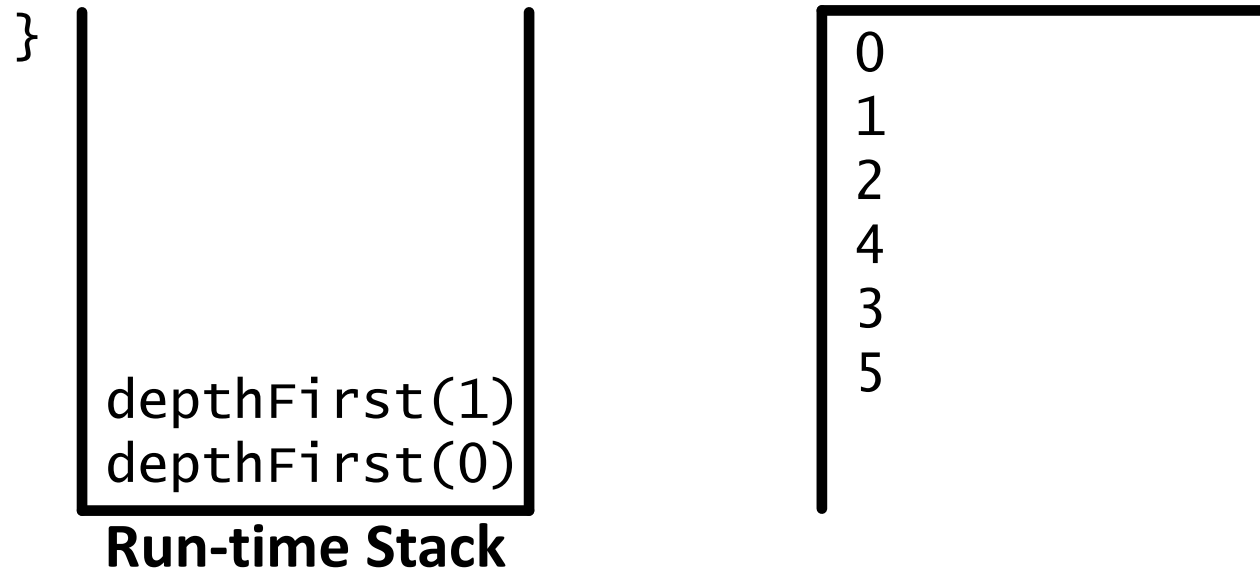
A diagram of an output stream represented as a vertical rectangle. Inside the rectangle, the following numbers are listed from top to bottom: 0, 1, 2, 4, 3, and 5.

```
0  
1  
2  
4  
3  
5
```



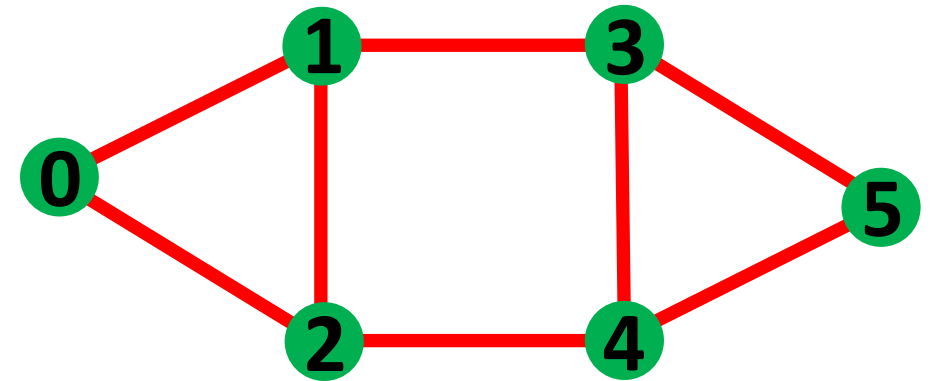
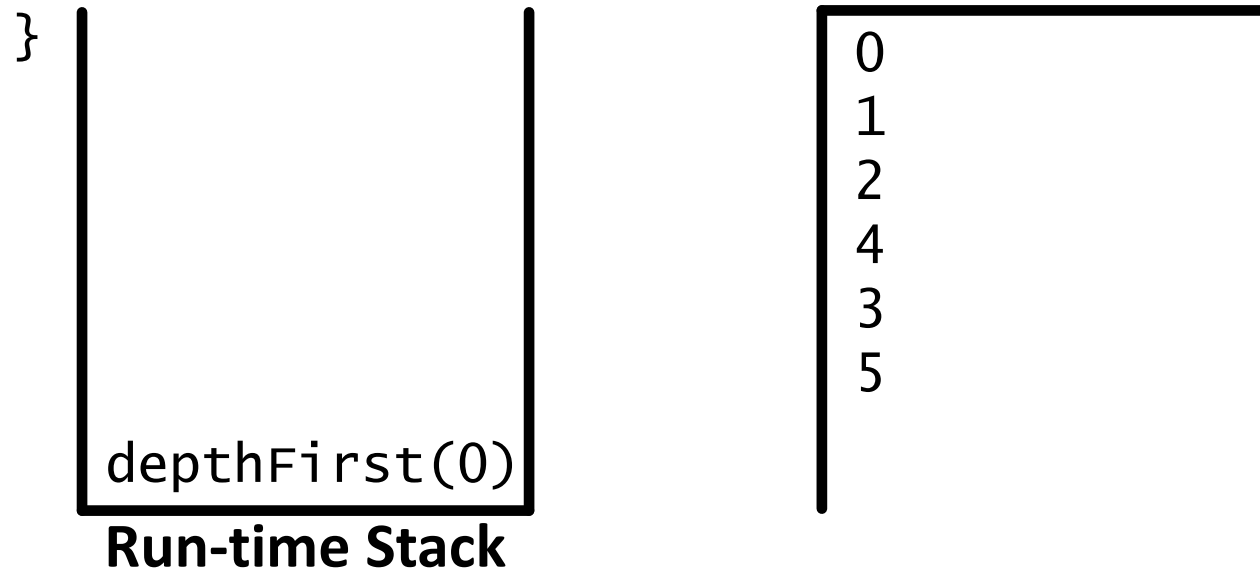
Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Graphs - Traversal

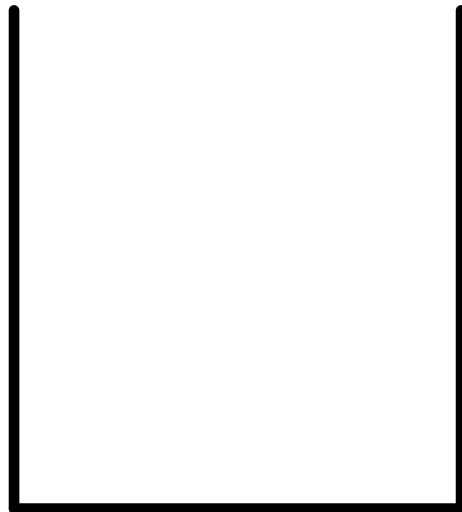
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

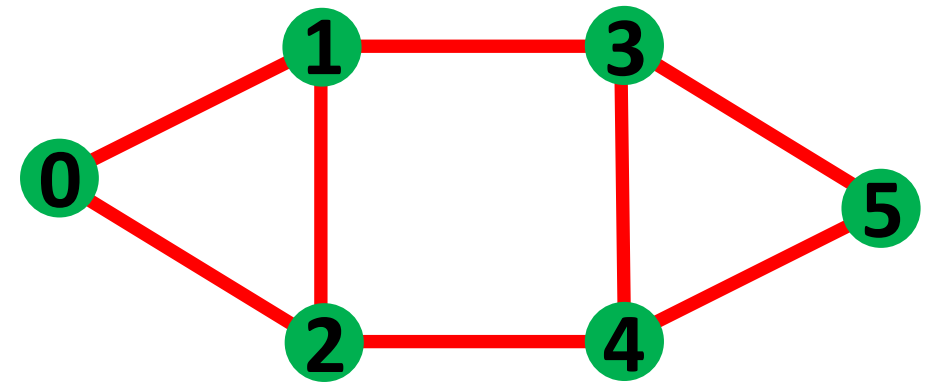
}



Run-time Stack

Output

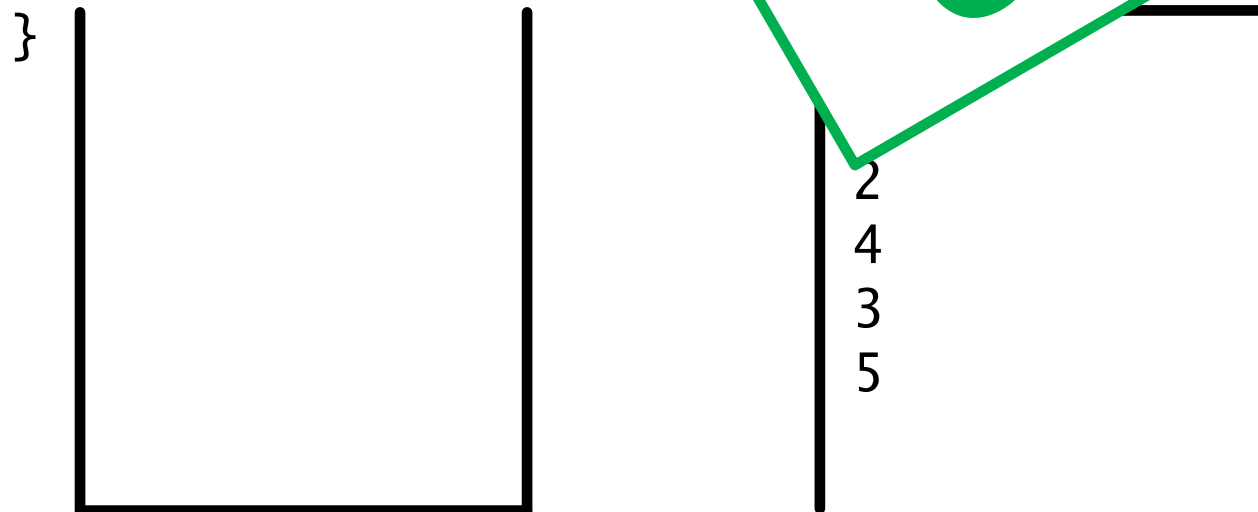
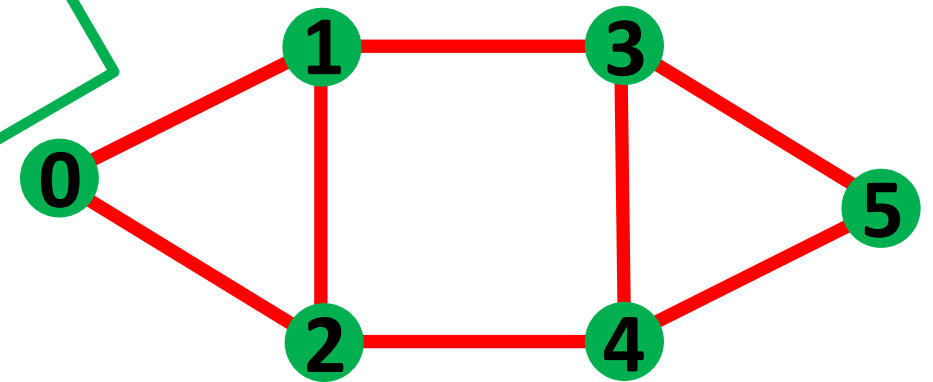
0
1
2
4
3
5



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n))  
        if (!visited[neighbor])  
            depthFirst(neighbor);  
}
```

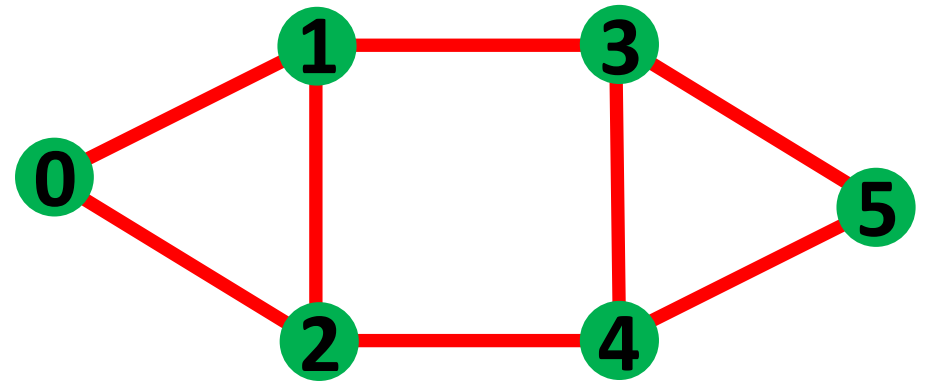
CODE



Run-time Stack

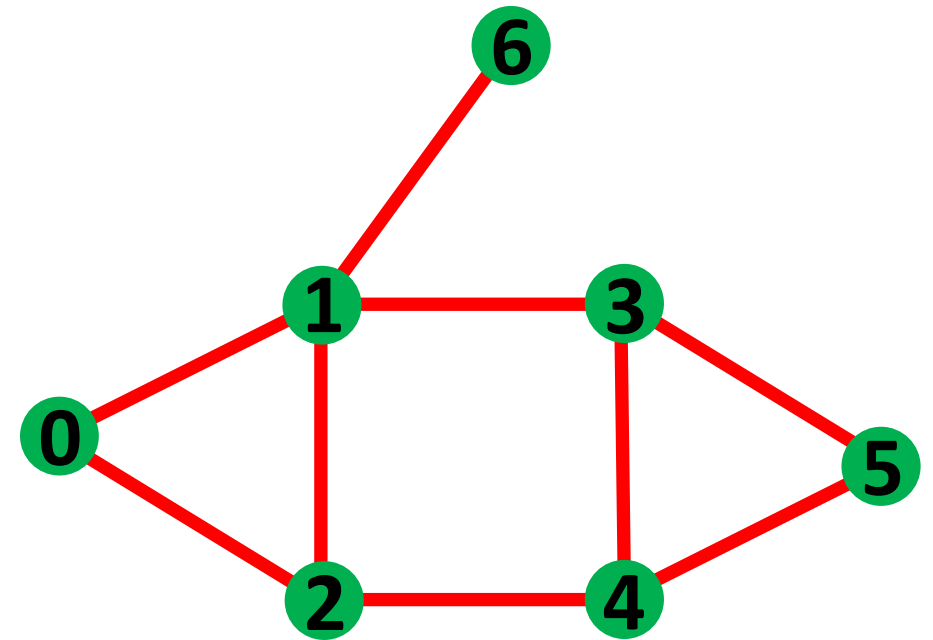
Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Graphs - Traversal

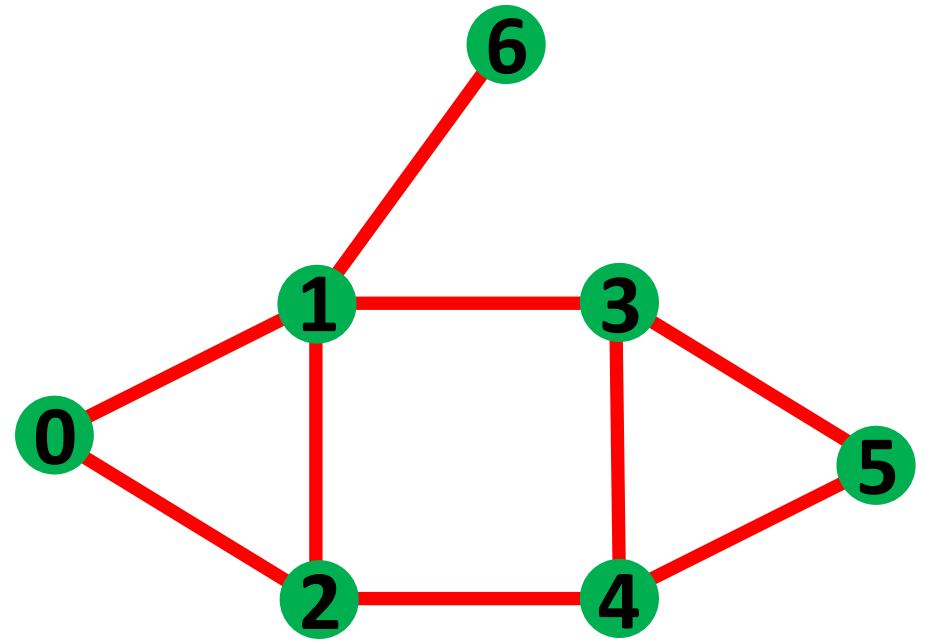
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

```
depthFirst(5)  
depthFirst(3)  
depthFirst(4)  
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Run-time Stack

Output

```
0  
1  
2  
4  
3  
5
```



Graphs - Traversal

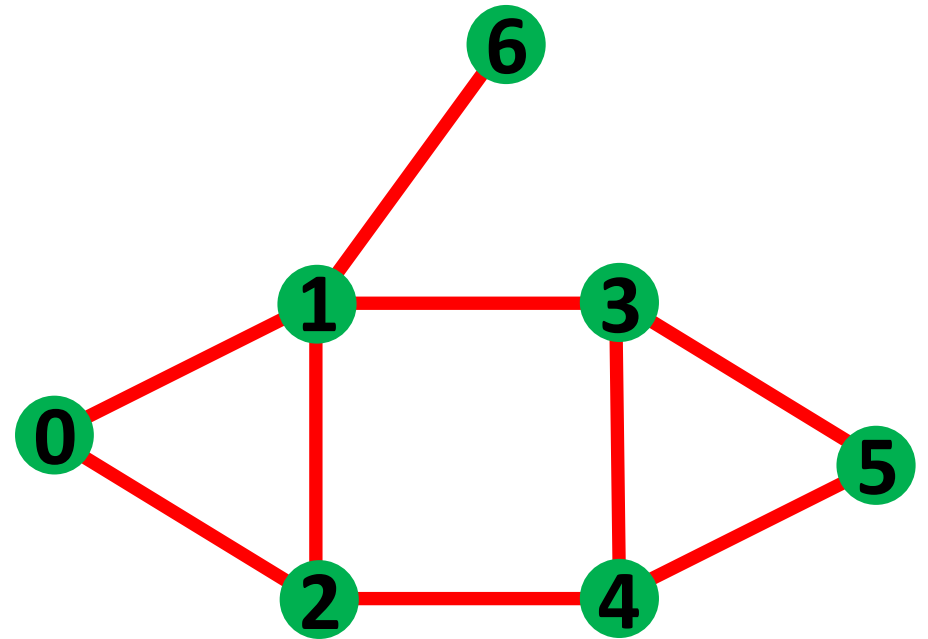
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

depthFirst(3)
depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4
3
5



Graphs - Traversal

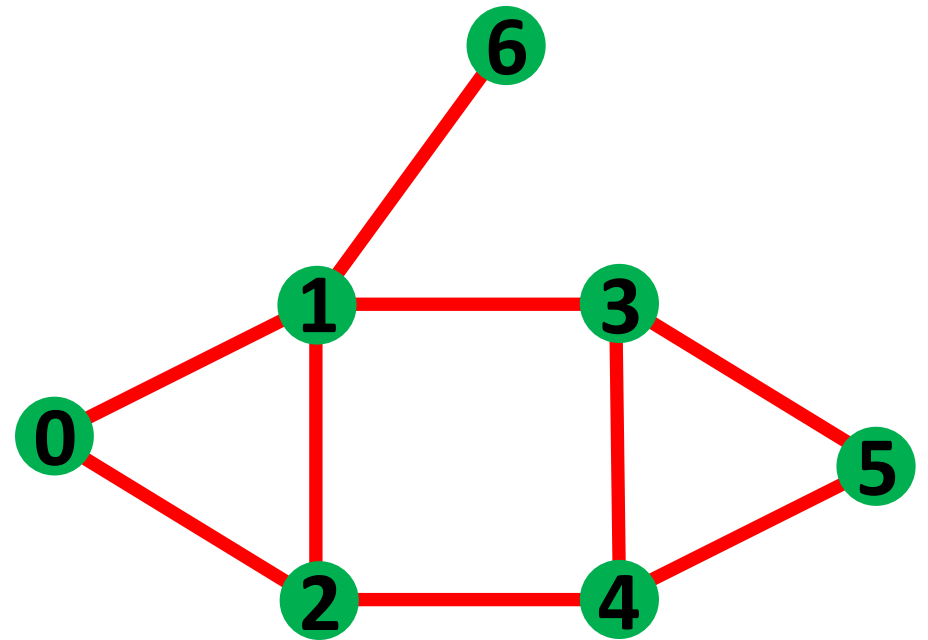
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4
3
5



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

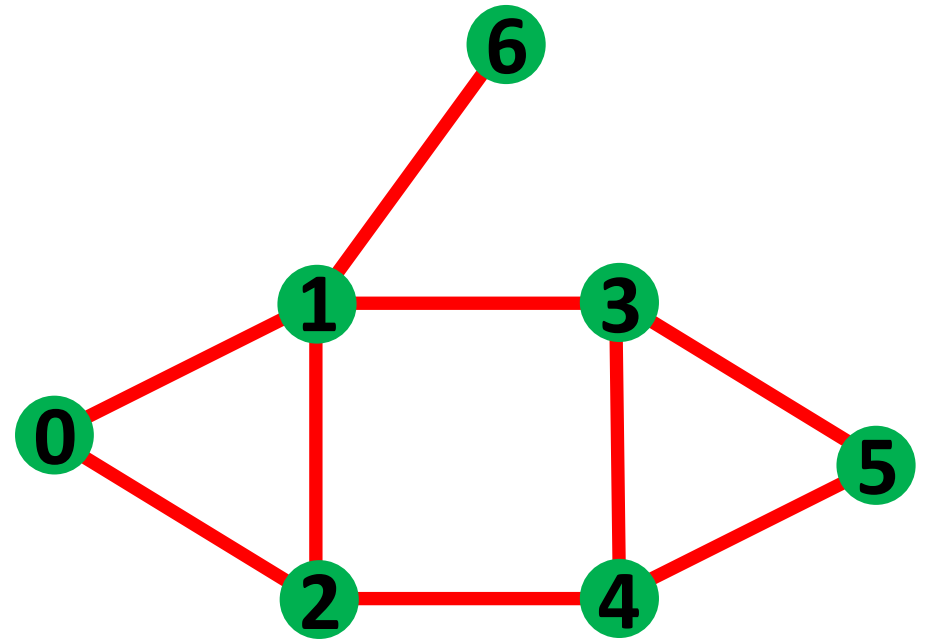
}

depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4
3
5



Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

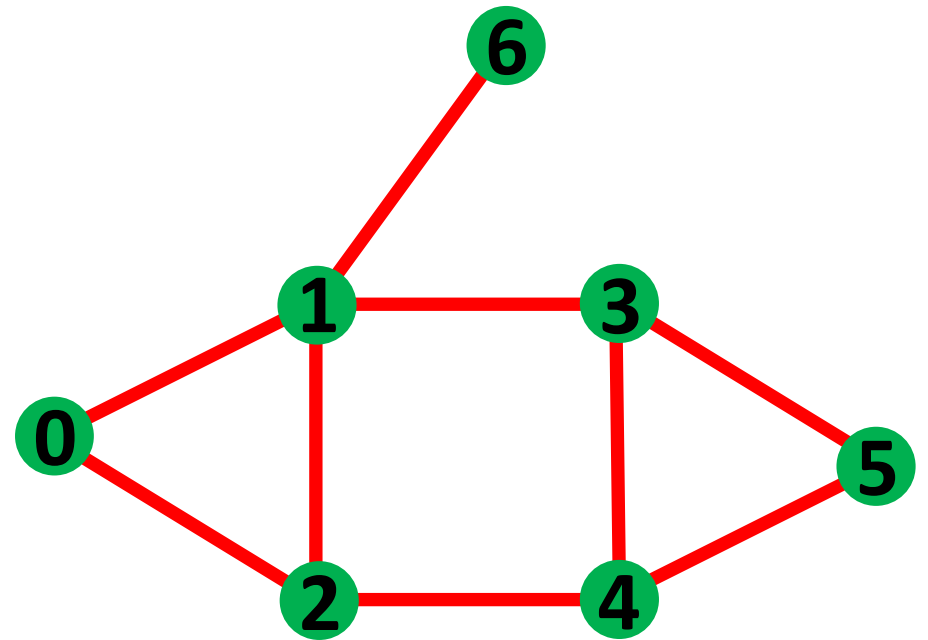
}

depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4
3
5



Graphs - Traversal

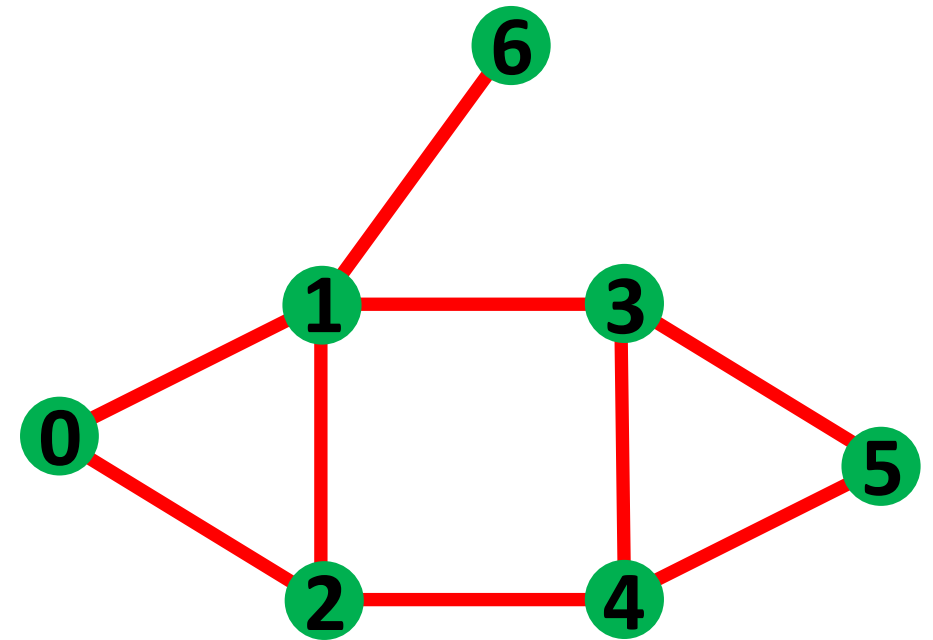
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

depthFirst(6)
depthFirst(1)
depthFirst(0)

Run-time Stack

Output

0
1
2
4
3
5



Graphs - Traversal

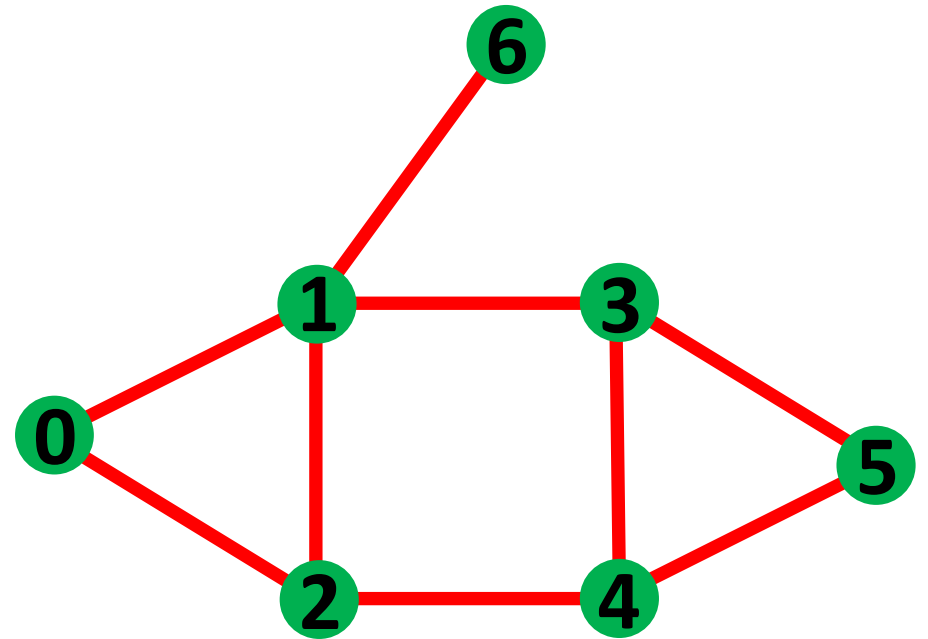
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

depthFirst(6)
depthFirst(1)
depthFirst(0)

Run-time Stack

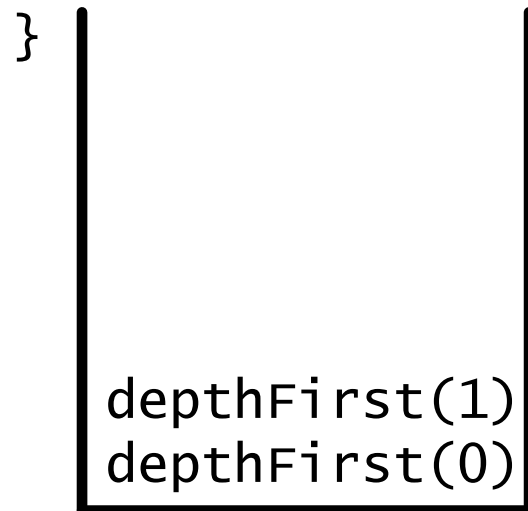
Output

0
1
2
4
3
5
6



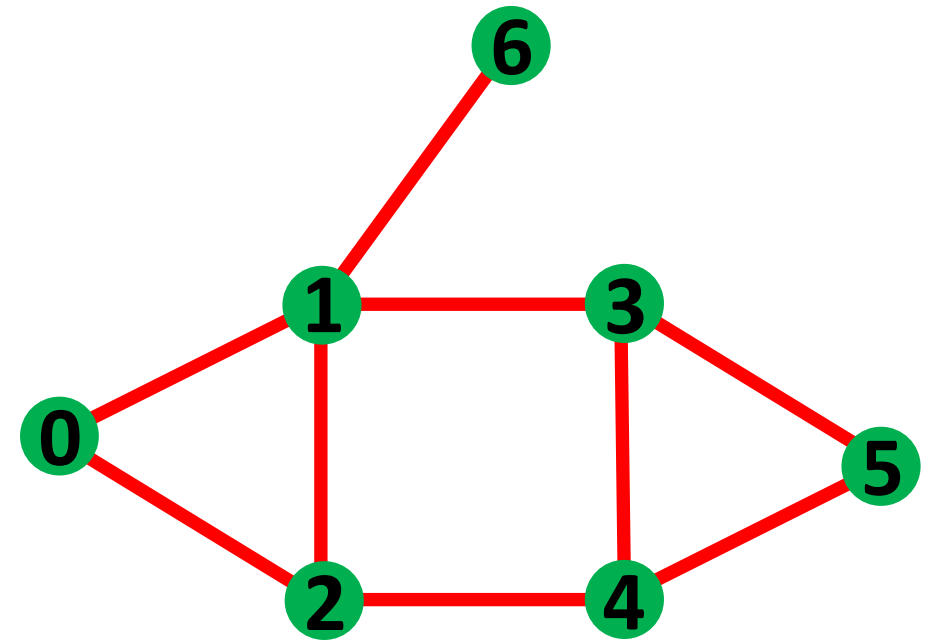
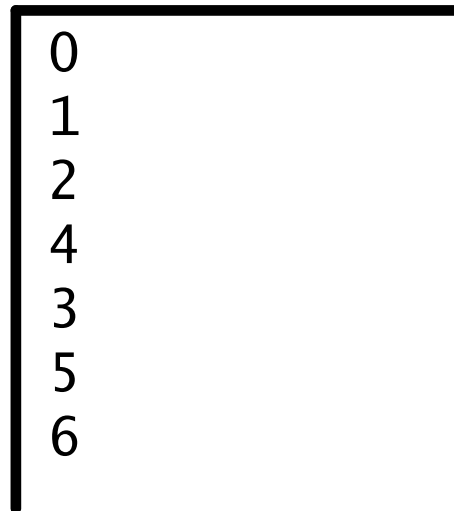
Graphs - Traversal

```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



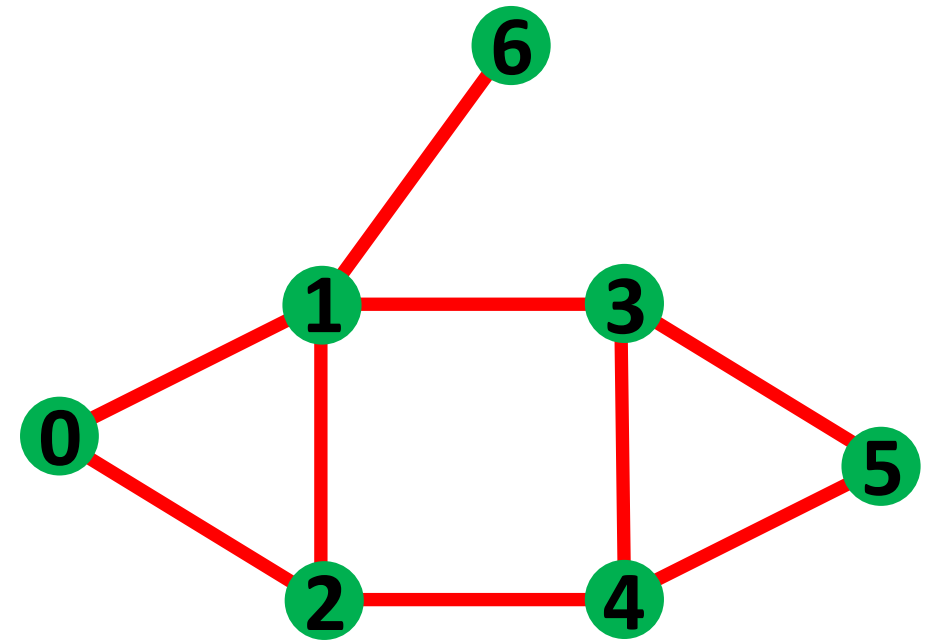
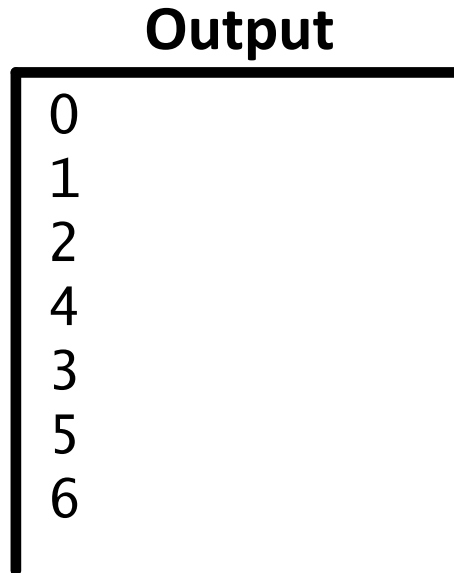
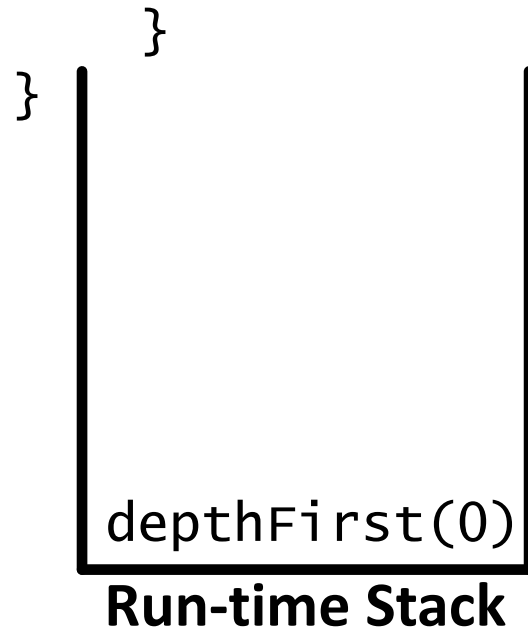
Run-time Stack

Output



Graphs - Traversal

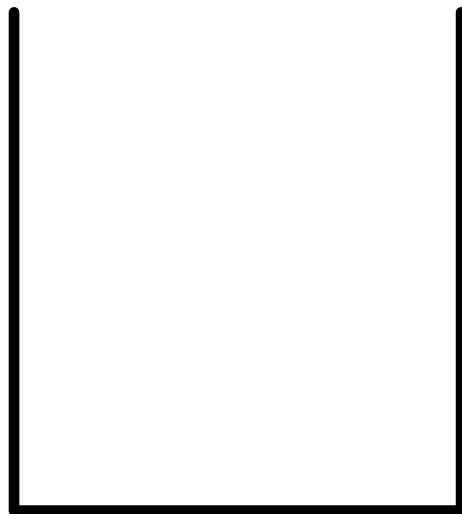
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```



Graphs - Traversal

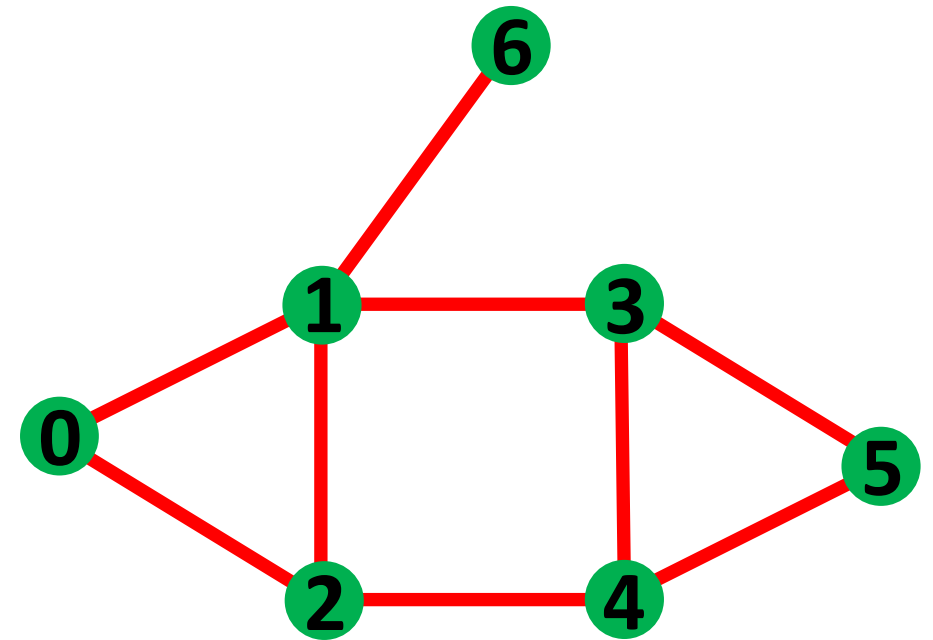
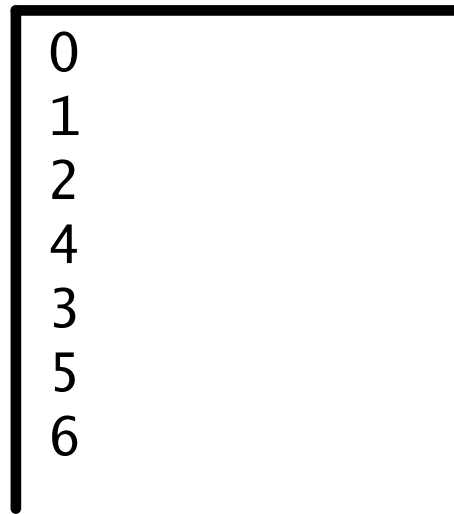
```
private boolean visited[] = new boolean[getNumVertices()];  
public void depthFirst(int n) {  
    System.out.println(n);  
    visited[n] = true;  
    for (int neighbor : getNeighbors(n)) {  
        if (!visited[neighbor]) {  
            depthFirst(neighbor);  
        }  
    }  
}
```

}



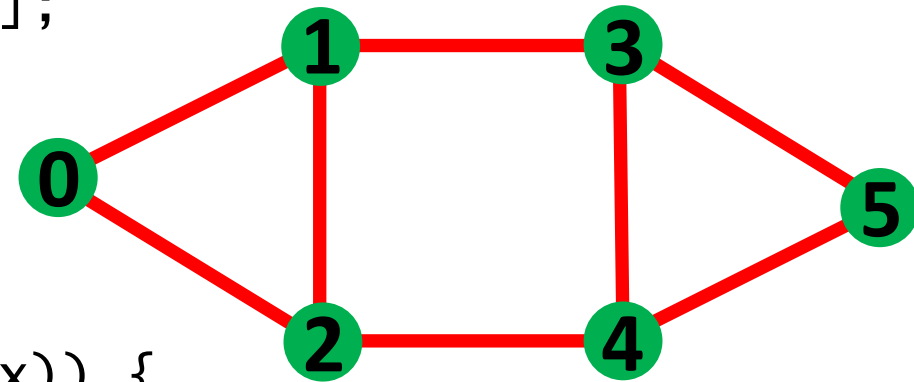
Run-time Stack

Output



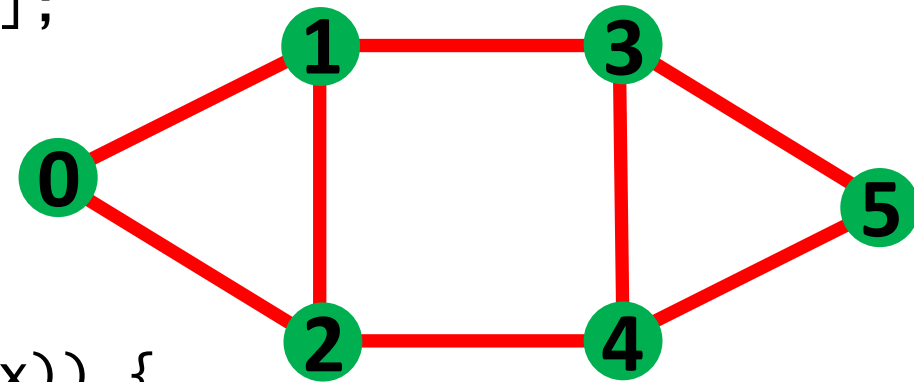
Graphs - Paths

```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}  
public boolean reachable(int endVertex) {  
    return visited[endVertex];  
}
```



Graphs - Paths

```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}  
public boolean reachable(int endVertex) {  
    return visited[endVertex];  
}
```



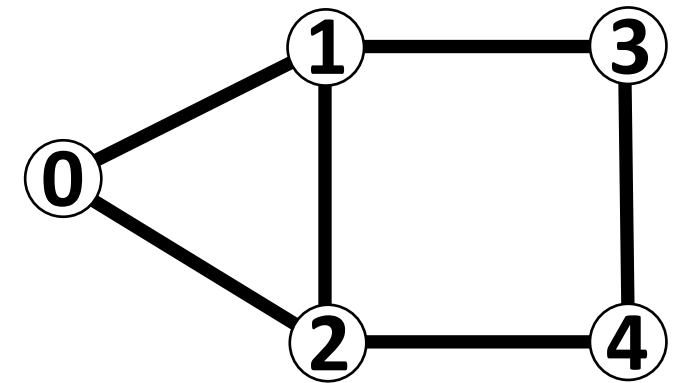
**How do we get actual
paths between vertices?**

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```



Run-time Stack

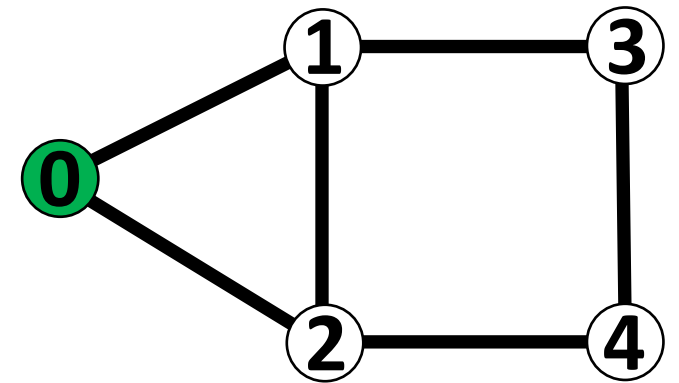


Graphs - Paths

```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(0)

Run-time Stack

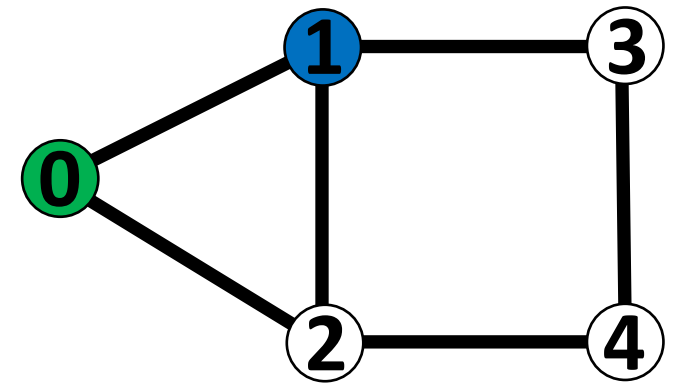


Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(1)
depthFirst(0)

Run-time Stack

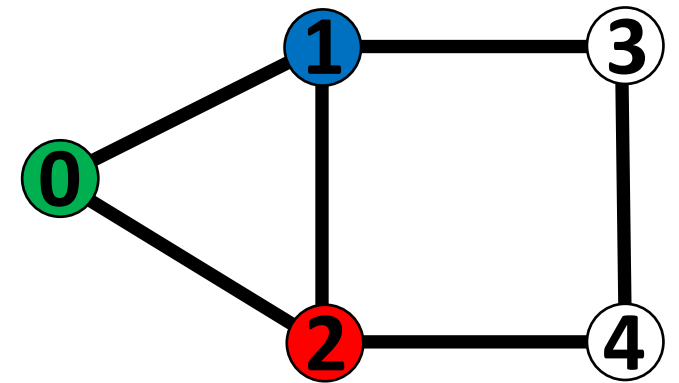


Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack



Graphs - Paths

```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

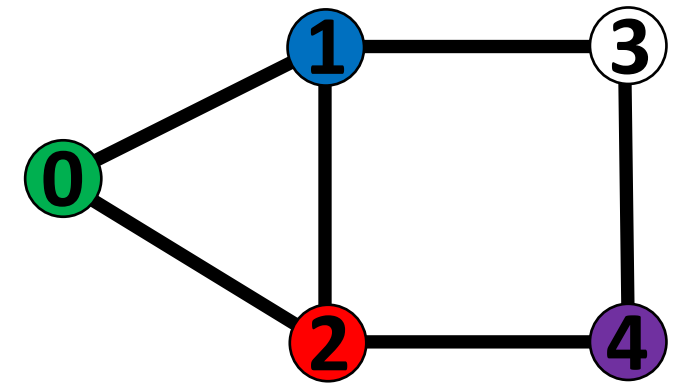
depthFirst(4)

depthFirst(2)

depthFirst(1)

depthFirst(0)

Run-time Stack



Graphs - Paths

```
private boolean[] visited;

public DepthFirstSearch(Graph graph, int startVertex) {
    visited = new boolean[graph.getNumVertices()];
    dfs(graph, startVertex);
}

private void dfs(Graph graph, int vertex) {
    visited[vertex] = true;
    for (int neighbor : graph.getNeighbors(vertex)) {
        if (!visited[neighbor]) {
            dfs(graph, neighbor);
        }
    }
}
```

depthFirst(3)

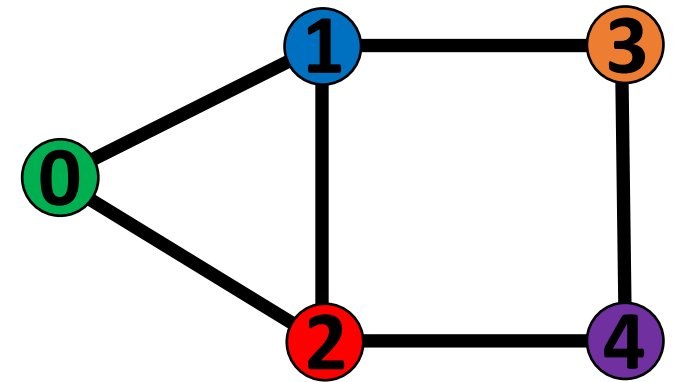
depthFirst(4)

depthFirst(2)

depthFirst(1)

depthFirst(0)

Run-time Stack



Was a path identified when determining that 0 and 3 are connected?

Graphs - Paths

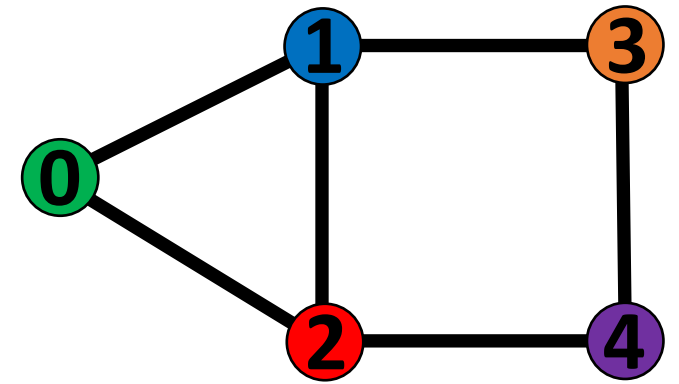
```
private boolean[] visited;

public DepthFirstSearch(Graph graph, int startVertex) {
    visited = new boolean[graph.getNumVertices()];
    dfs(graph, startVertex);
}

private void dfs(Graph graph, int vertex) {
    visited[vertex] = true;
    for (int neighbor : graph.getNeighbors(vertex)) {
        if (!visited[neighbor]) {
            dfs(graph, neighbor);
        }
    }
}
```

Run-time Stack

- depthFirst(3)
- depthFirst(4)
- depthFirst(2)
- depthFirst(1)
- depthFirst(0)



Was a path identified when determining that 0 and 3 are connected?

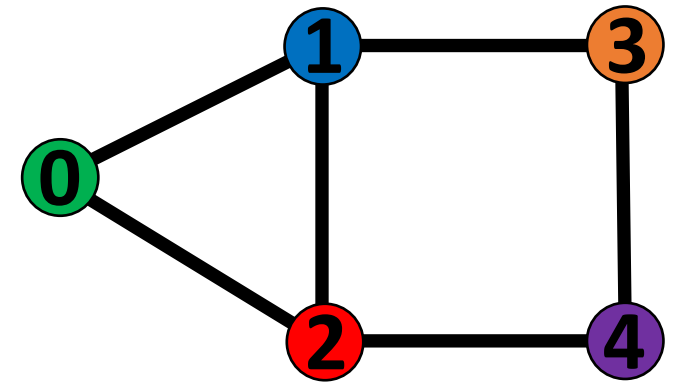
YES!

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

`depthFirst(0)`

Run-time Stack



Was a path identified when determining that 0 and 3 are connected?

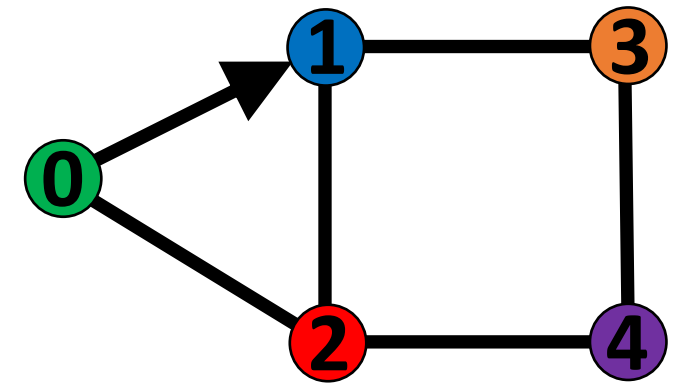
YES!

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(1)
depthFirst(0)

Run-time Stack



Was a path identified when determining that 0 and 3 are connected?

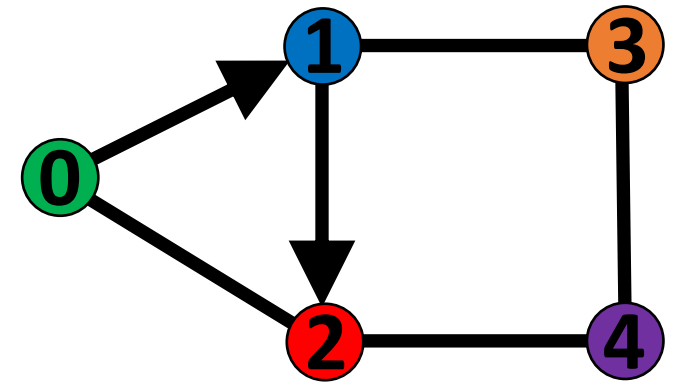
YES!

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack



Was a path identified when determining that 0 and 3 are connected?

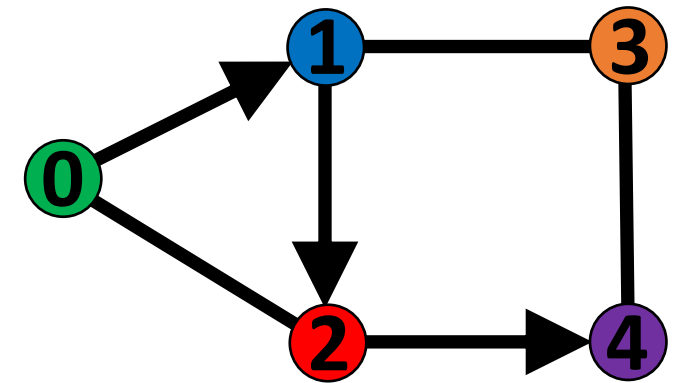
YES!

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack



Was a path identified when determining that 0 and 3 are connected?

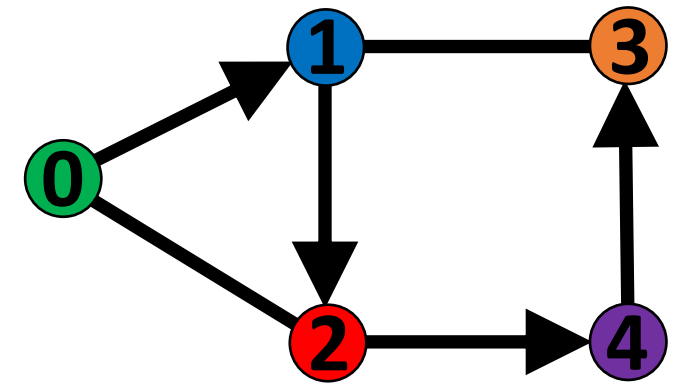
YES!

Graphs - Paths

```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(3)
depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack



Was a path identified when determining that 0 and 3 are connected?

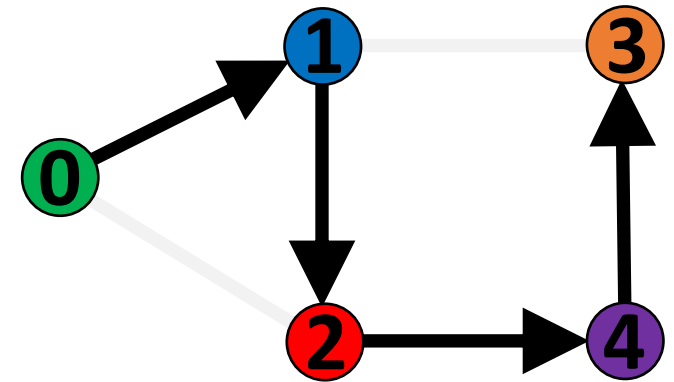
YES!

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

depthFirst(3)
depthFirst(4)
depthFirst(2)
depthFirst(1)
depthFirst(0)

Run-time Stack



Was a path identified when determining that 0 and 3 are connected?

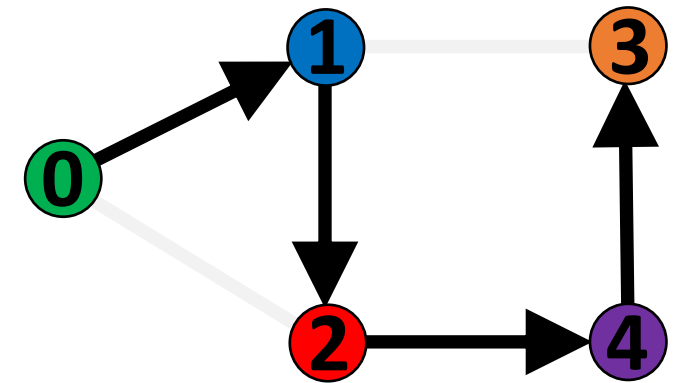
YES!

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

```
depthFirst(3)  
depthFirst(4)  
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Run-time Stack



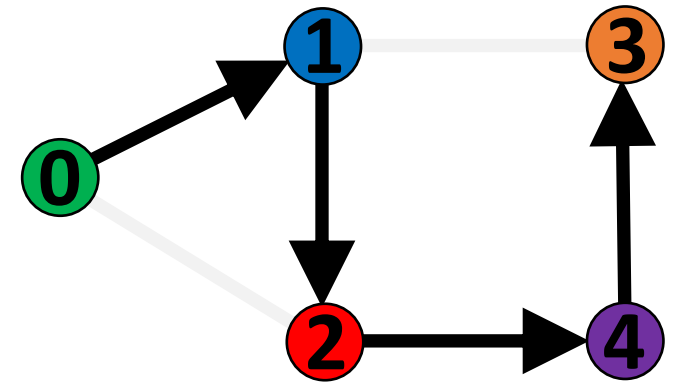
What else was identified?

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

```
depthFirst(3)  
depthFirst(4)  
depthFirst(2)  
depthFirst(1)  
depthFirst(0)
```

Run-time Stack

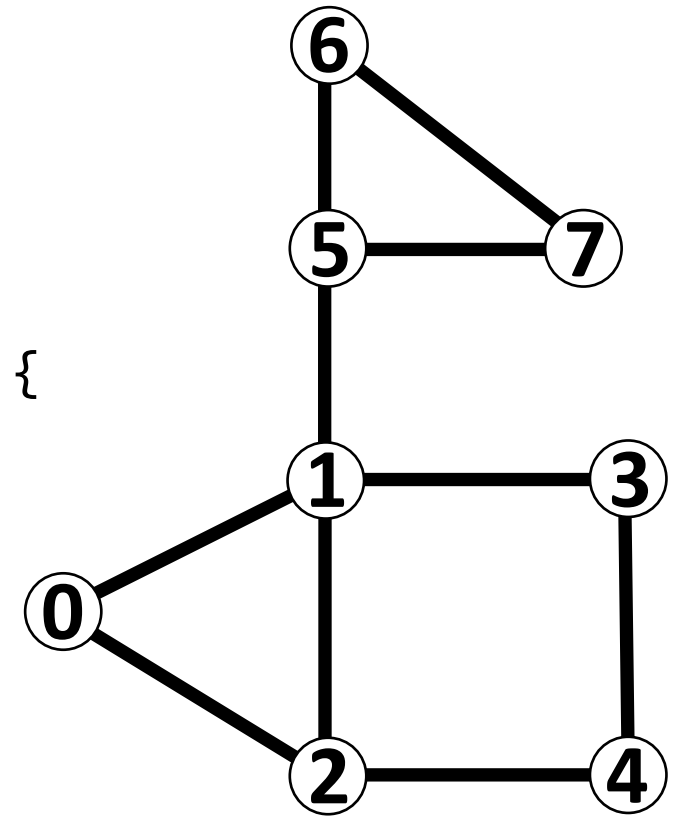


What else was identified?

A path from 0 to everything
connected to 0!

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

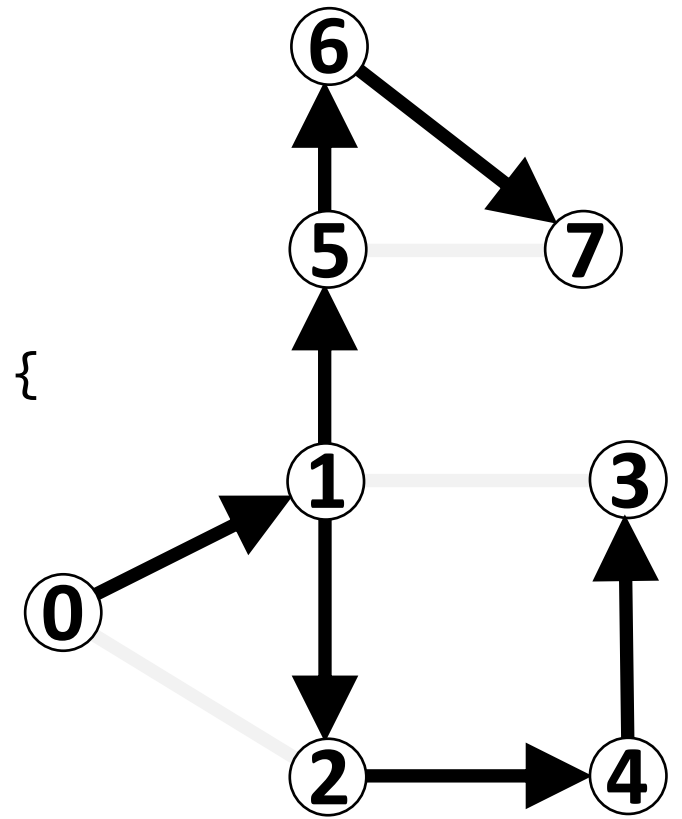


What else was identified?

**A path from 0 to everything
connected to 0!**

Graphs - Paths

```
private boolean[] visited;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

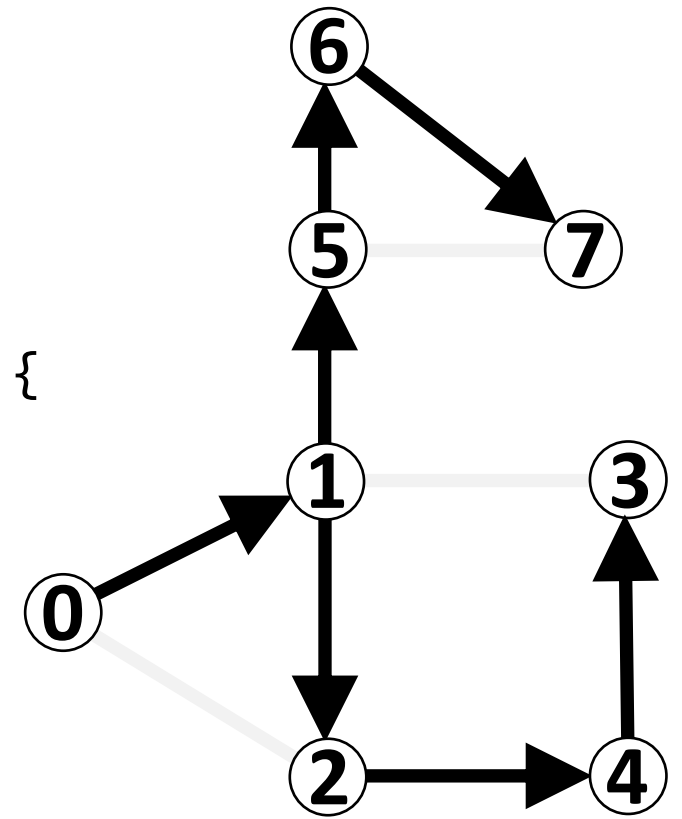


What else was identified?

A path from 0 to everything connected to 0!

Graphs - Paths

```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```



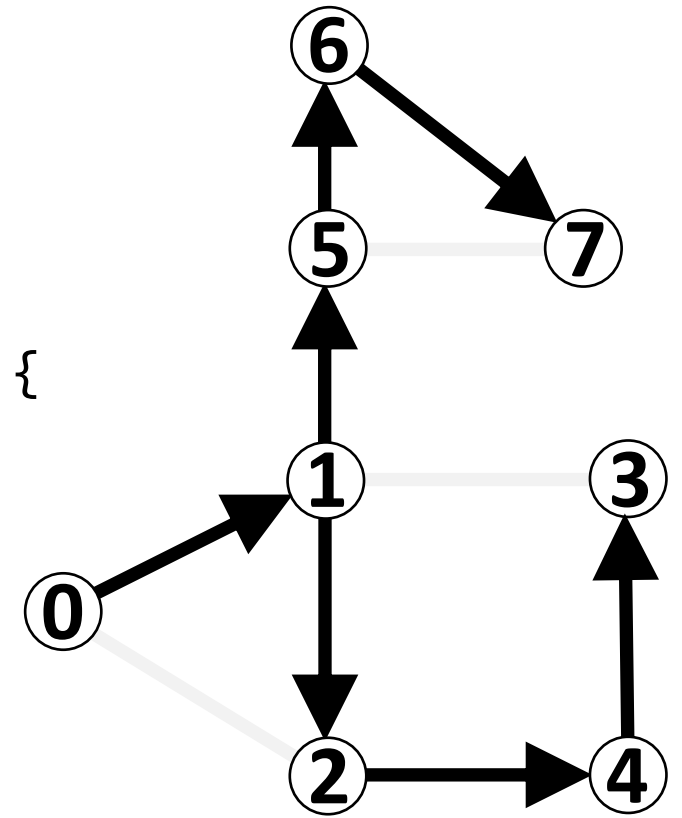
How can we store/compute these paths?

Graphs - Paths

```
private boolean[] visited;

public DepthFirstSearch(Graph graph, int startVertex) {
    visited = new boolean[graph.getNumVertices()];
    dfs(graph, startVertex);
}

private void dfs(Graph graph, int vertex) {
    visited[vertex] = true;
    for (int neighbor : graph.getNeighbors(vertex)) {
        if (!visited[neighbor]) {
            dfs(graph, neighbor);
        }
    }
}
```

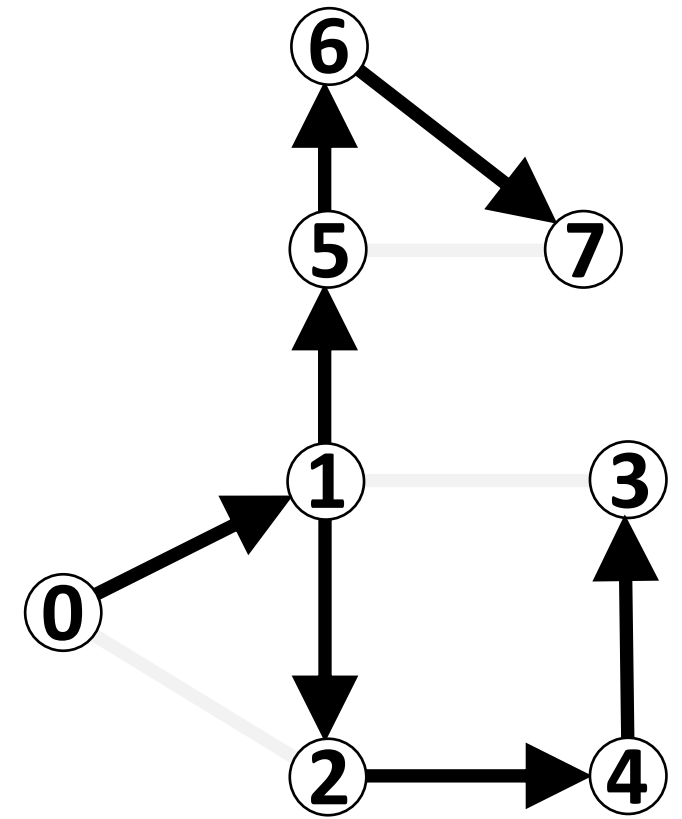
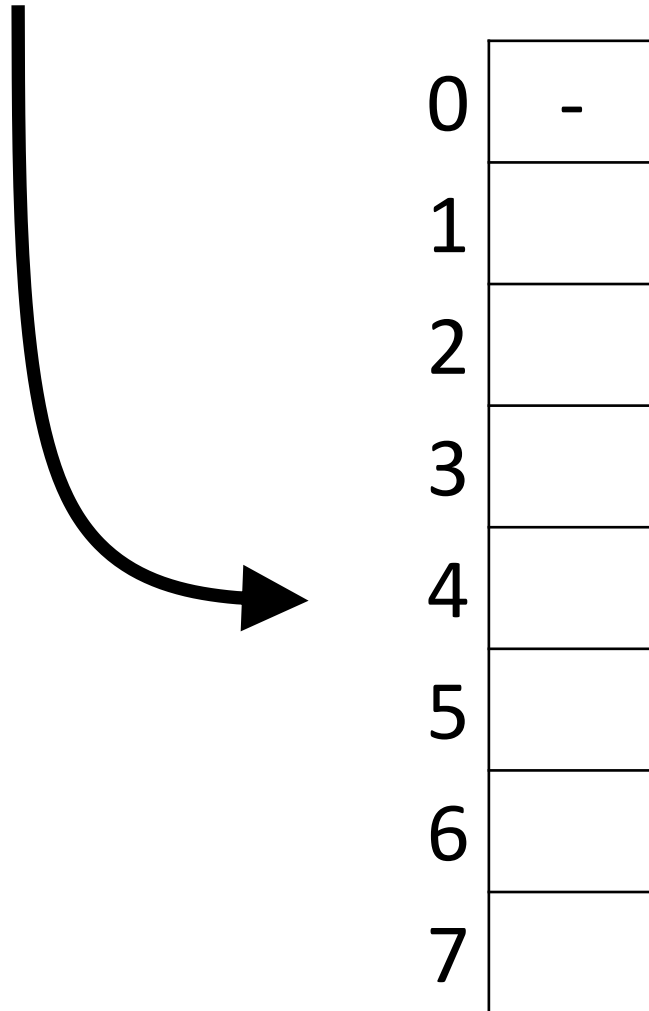


How can we store/compute these paths?

What if, for each vertex, we stored the previous vertex?

Graphs - Paths

`int[] previousVertex`

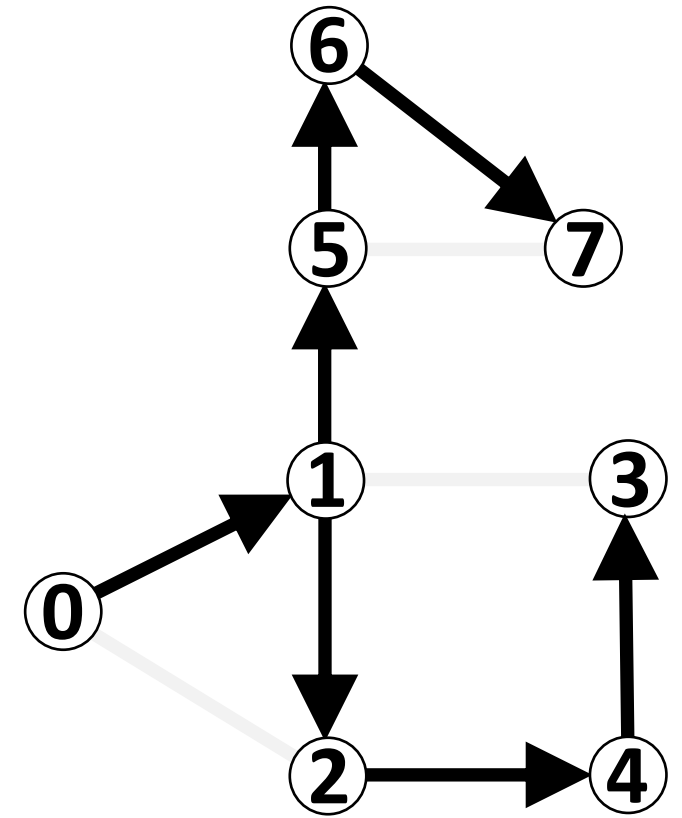
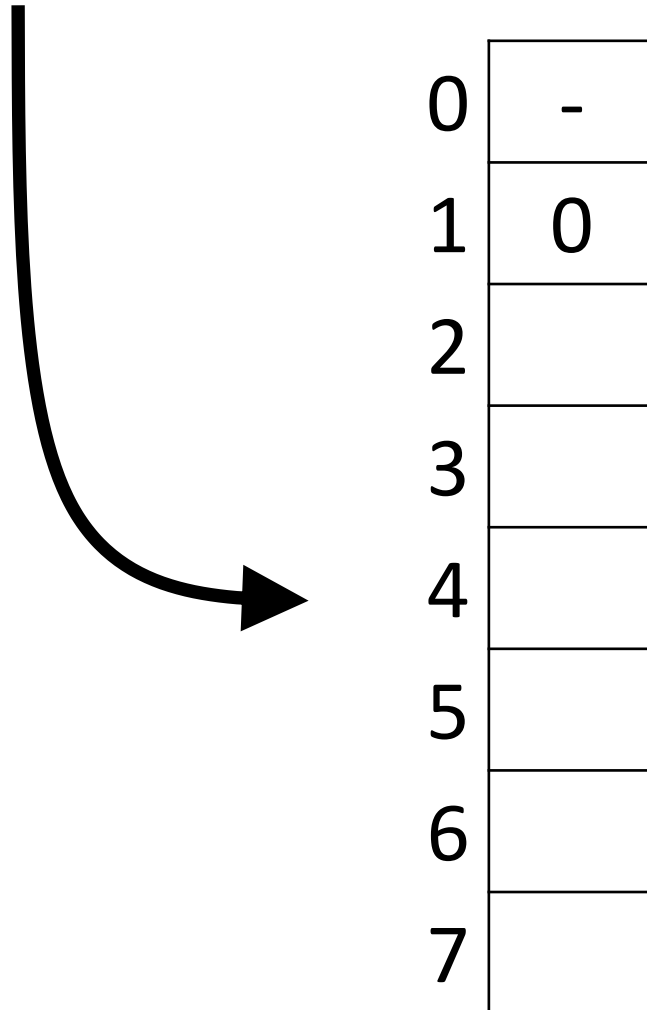


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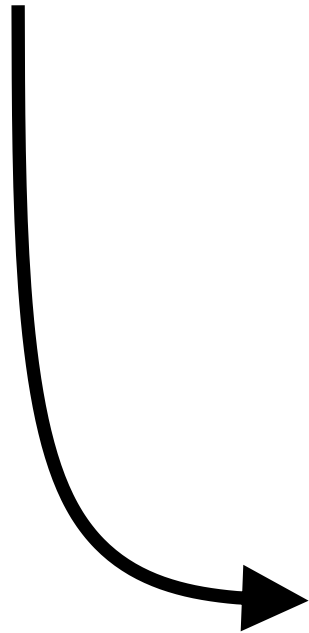


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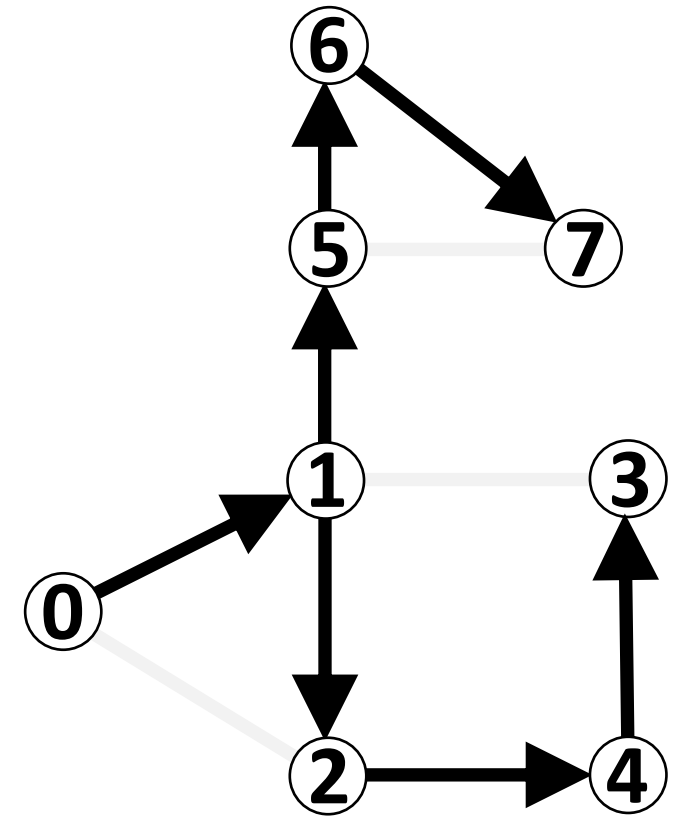
What if, for each vertex, we stored the previous vertex?

Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	
4	
5	
6	
7	

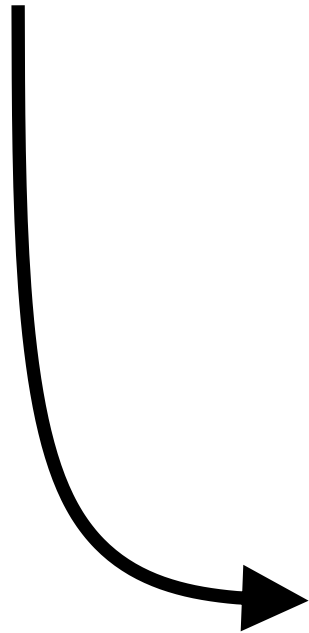


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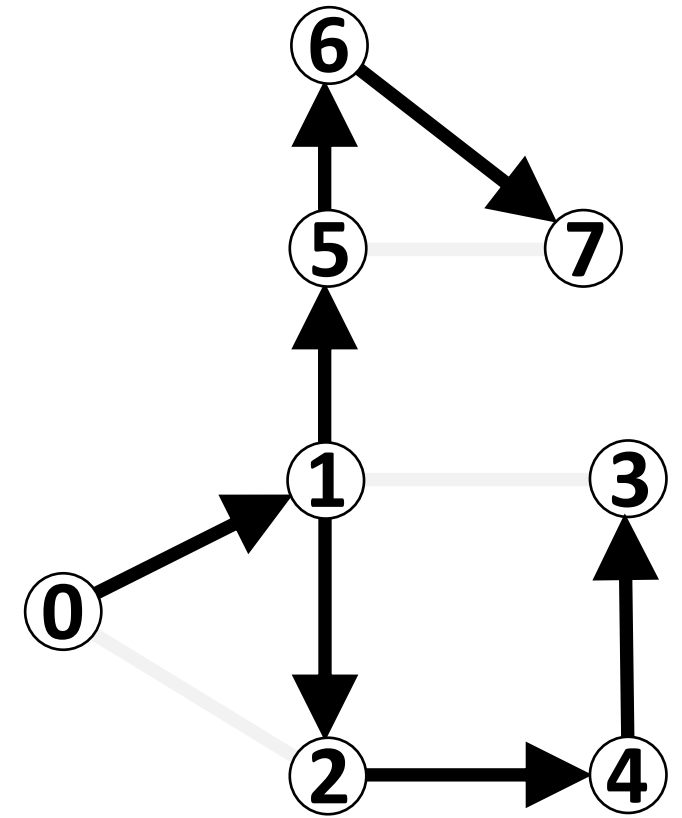
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Graphs - Paths

`int[] previousVertex`



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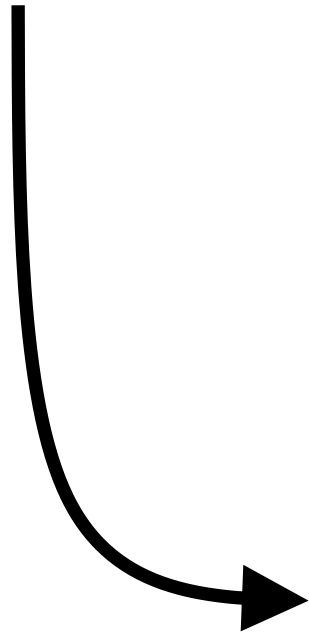


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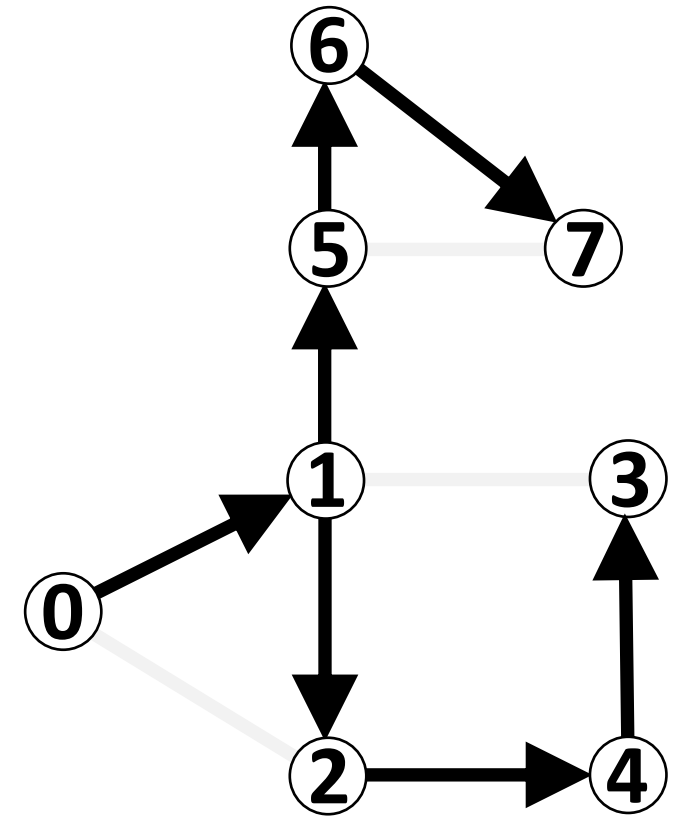
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Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	4
4	2
5	
6	
7	

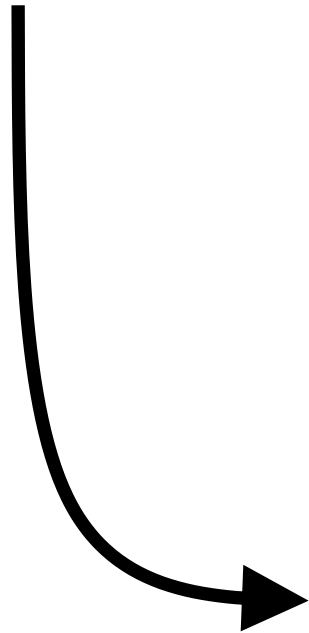


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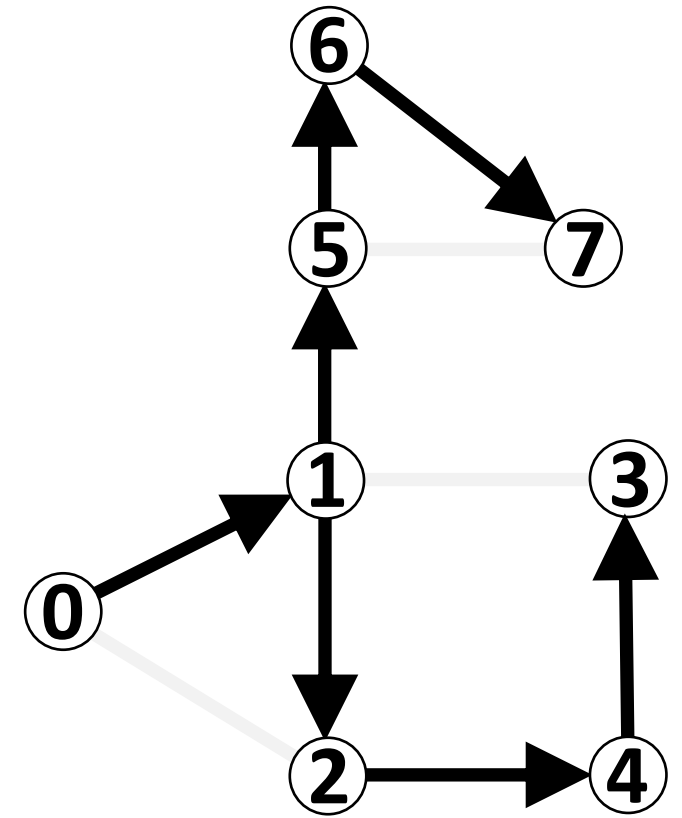
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Graphs - Paths

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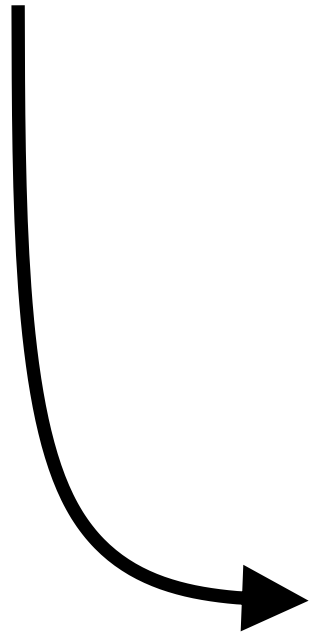


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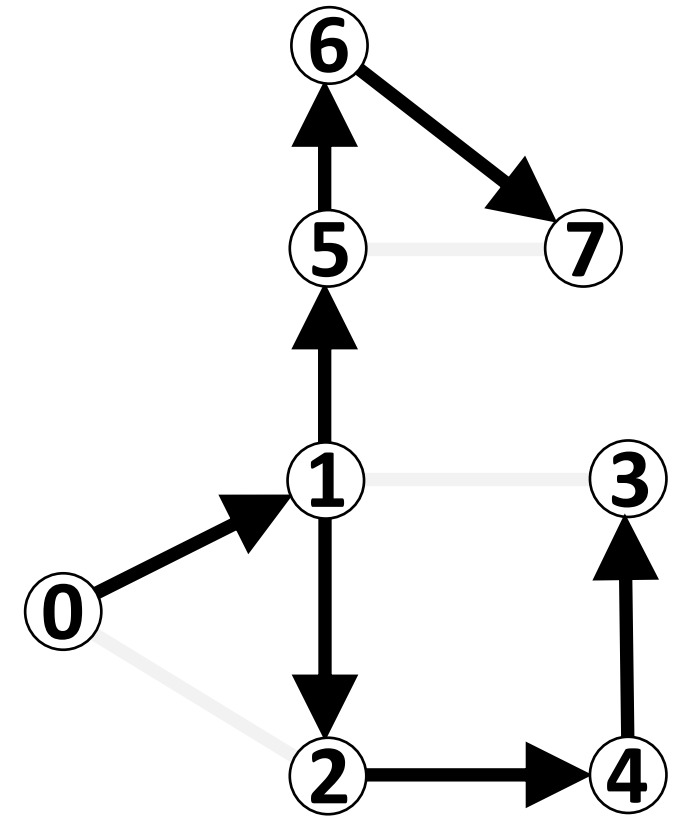
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Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	

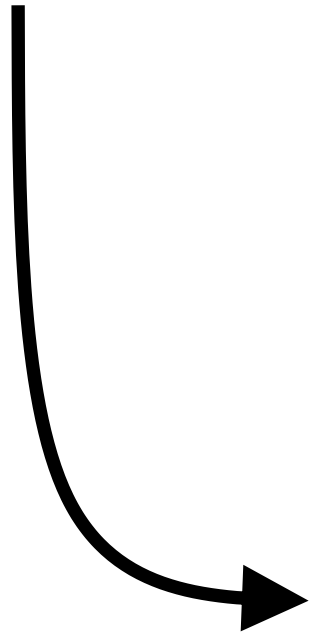


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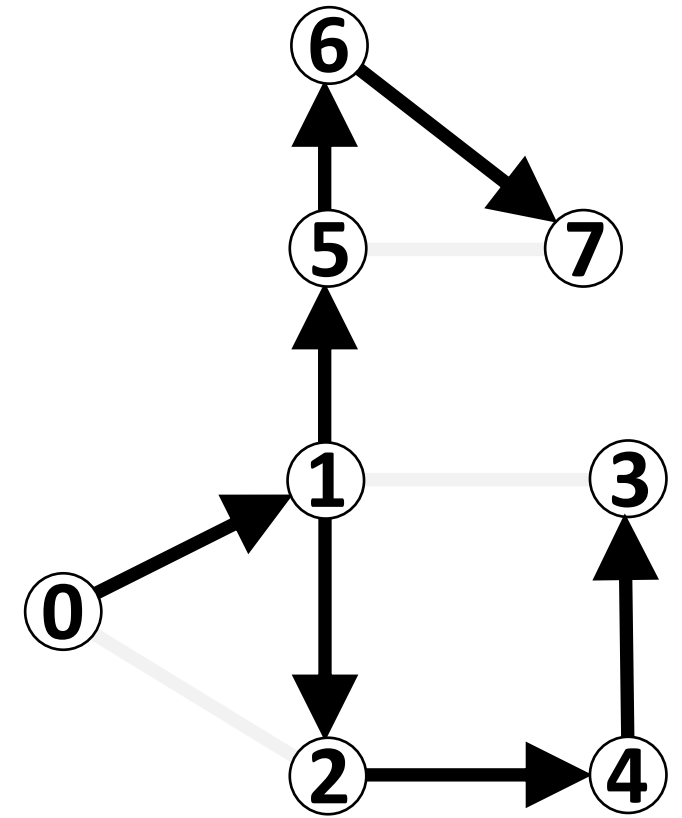
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Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6

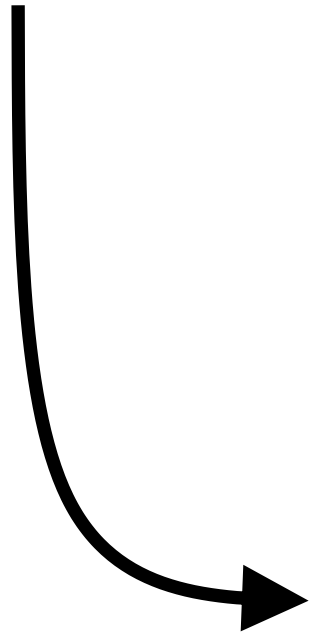


How can we store/compute these paths?

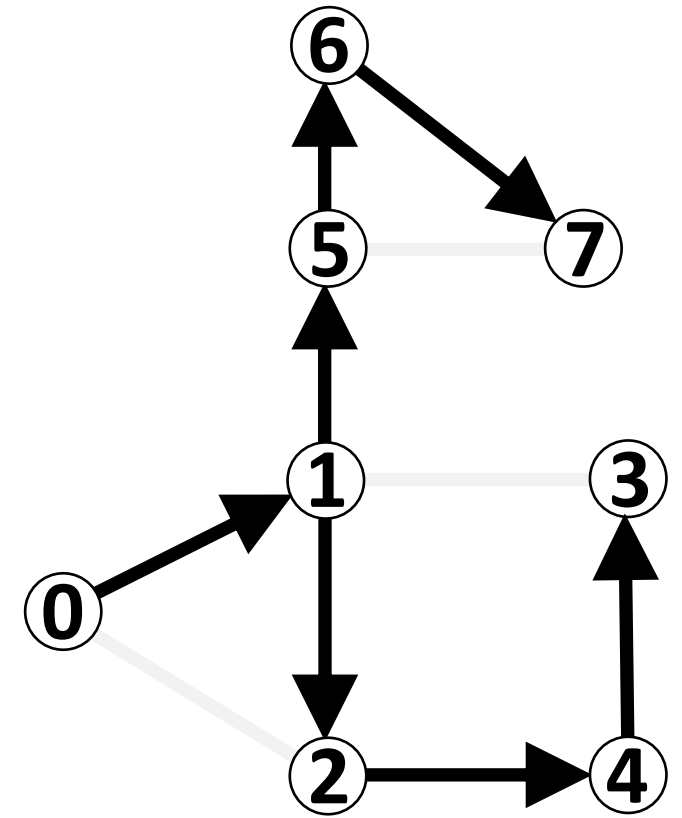
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Graphs - Paths

`int[] previousVertex`



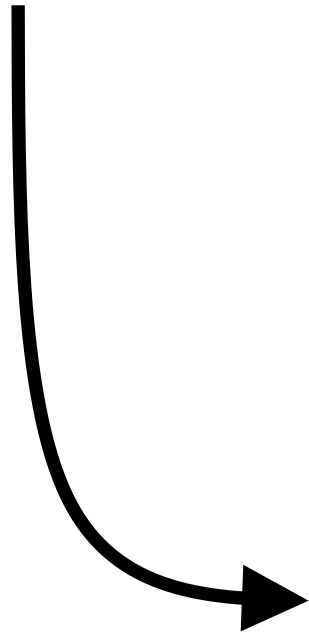
0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6



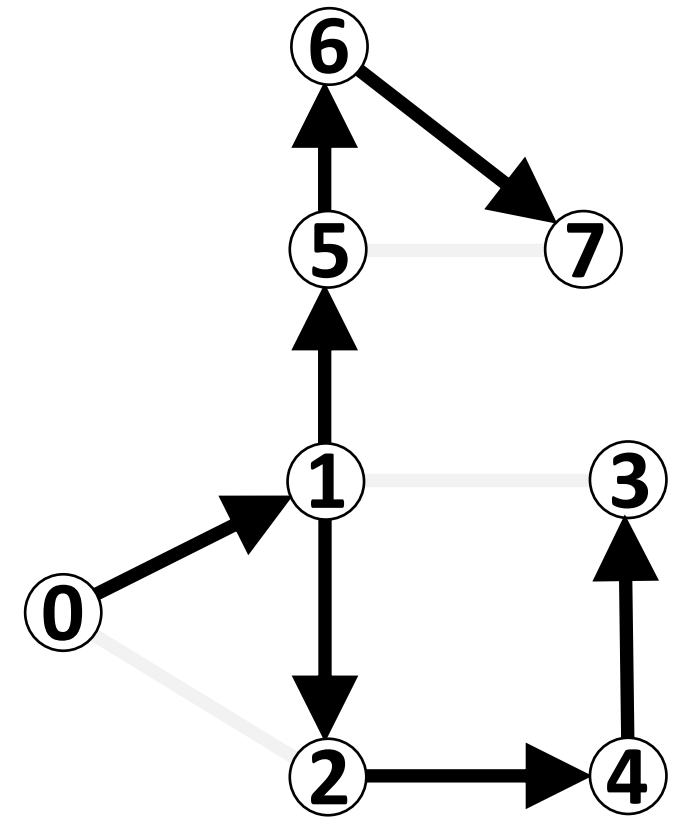
How do we determine the path from 0 to 6?

Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6

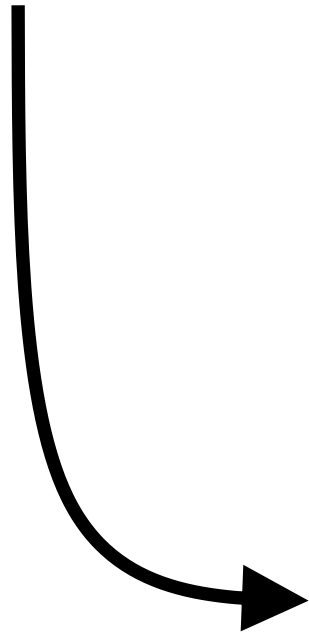


How do we determine the path from 0 to 6?

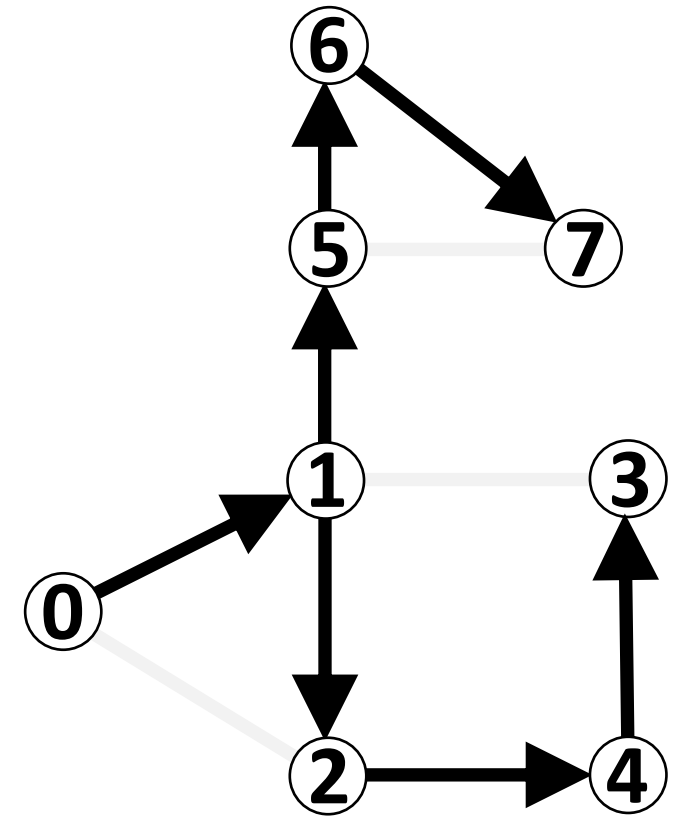
Start at vertex 6.

Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6

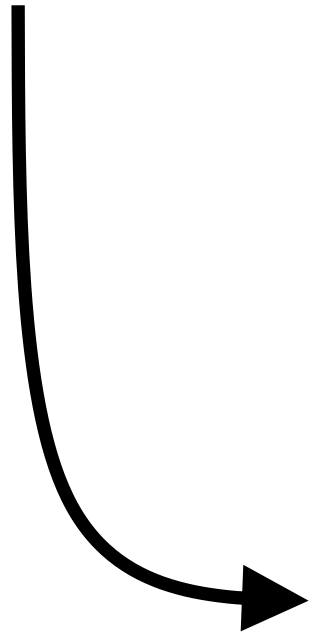


How do we determine the path from 0 to 6?

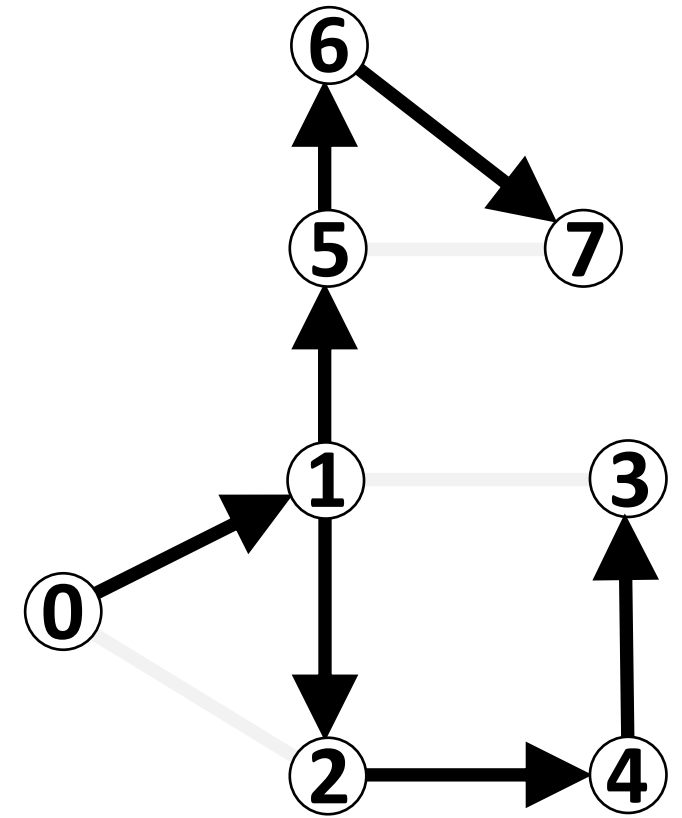
Start at vertex 6. Find its previous vertex.

Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6

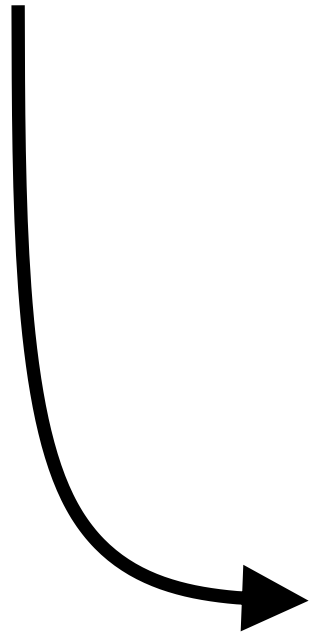


How do we determine the path from 0 to 6?

Start at vertex 6. Find its previous vertex. Find its previous vertex

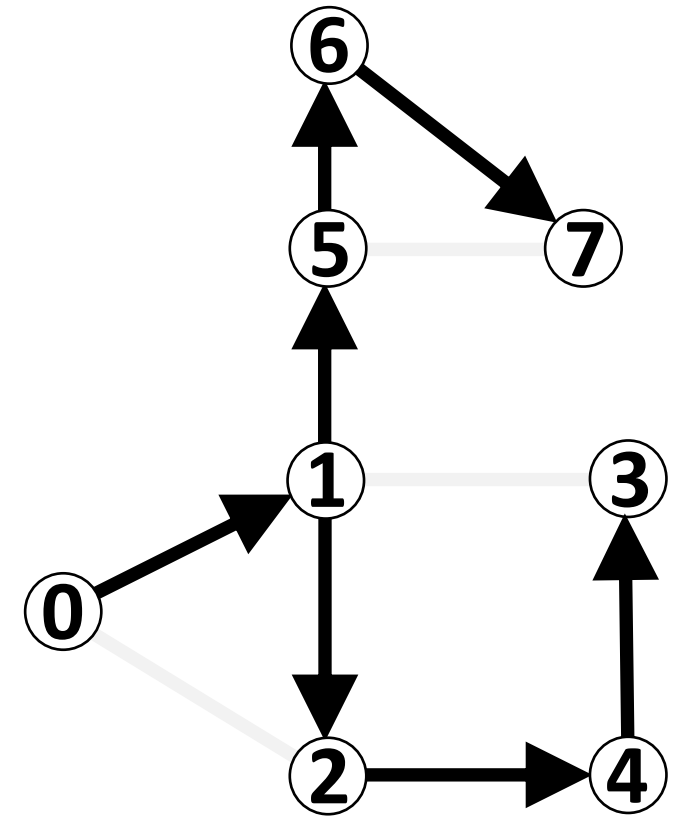
Graphs - Paths

`int[] previousVertex`



0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6

The table represents the 'previousVertex' array. The first column contains vertex indices from 0 to 7. The second column contains the index of the previous vertex in the path. The path from 0 to 6 is highlighted with green circles around the vertices 1, 5, and 6, and green arrows showing the sequence: 0 → 1 → 2 → 4 → 5 → 6.

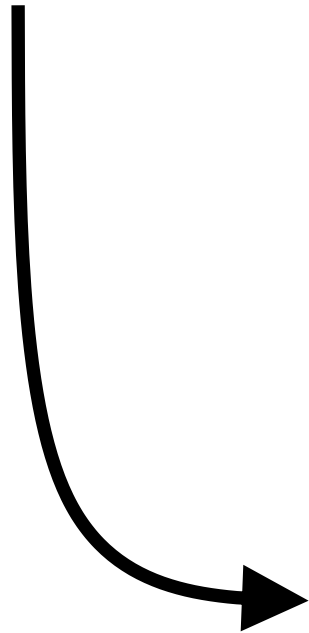


How do we determine the path from 0 to 6?

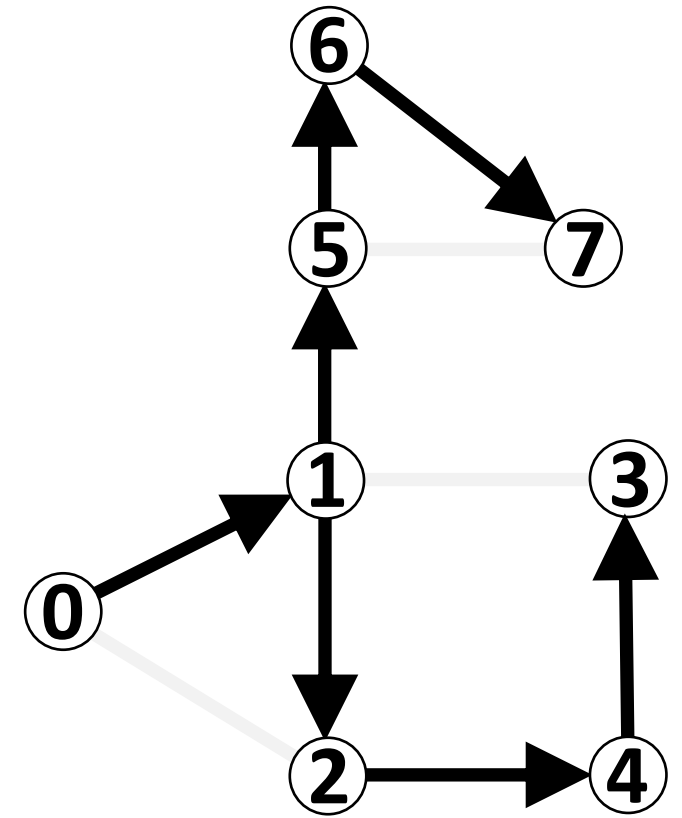
Start at vertex 6. Find its previous vertex. Find its previous vertex... until we get back to the start (0).

Graphs - Paths

`int[] previousVertex`



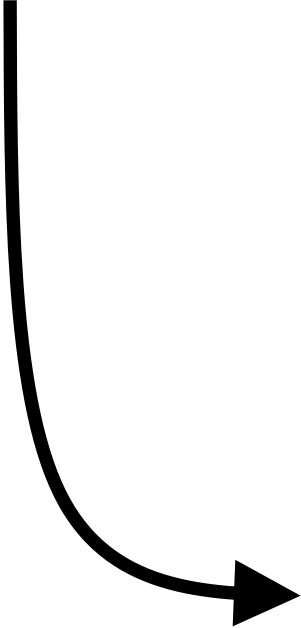
0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6



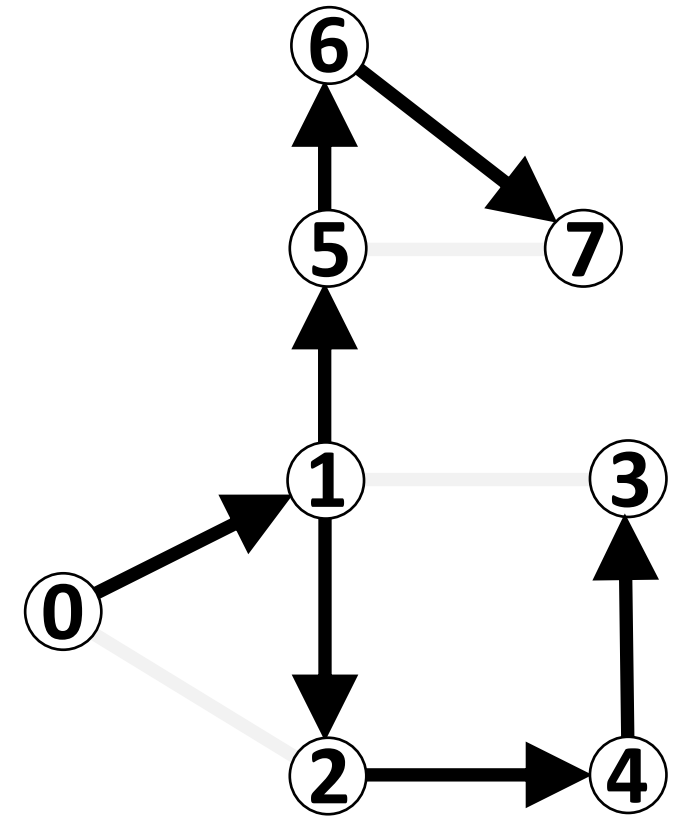
How do we determine the path from 0 to 3?

Graphs - Paths

`int[] previousVertex`



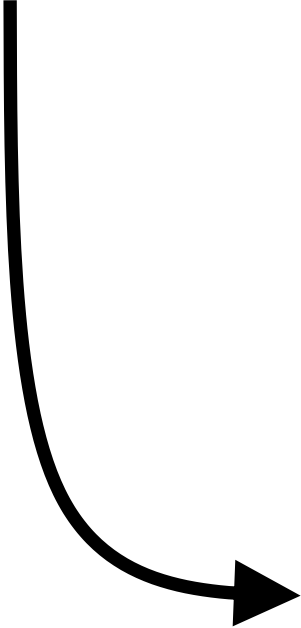
0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6



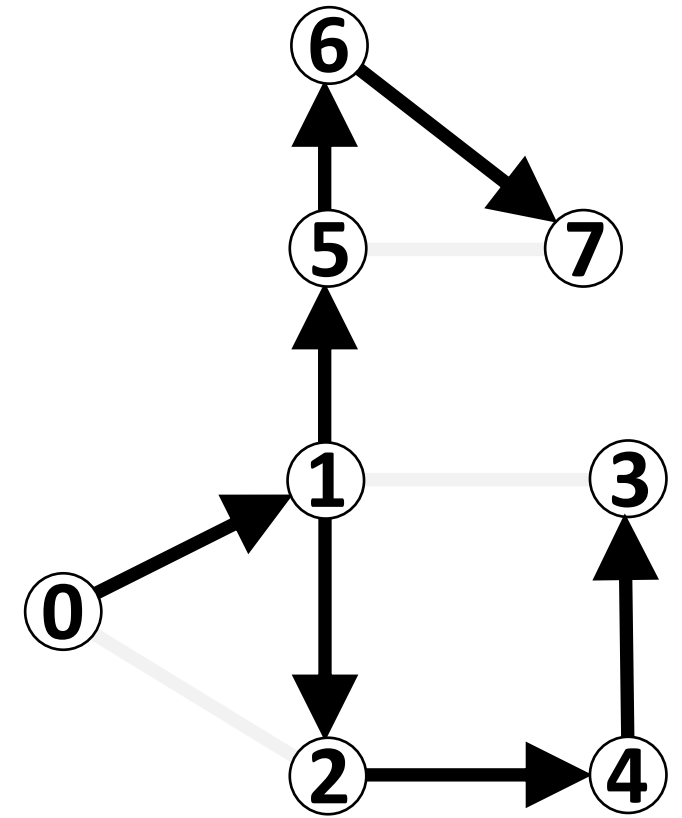
How do we determine the path from 0 to 3?

Graphs - Paths

`int[] previousVertex`



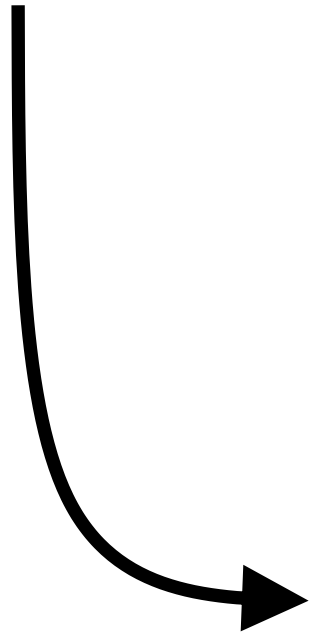
0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6



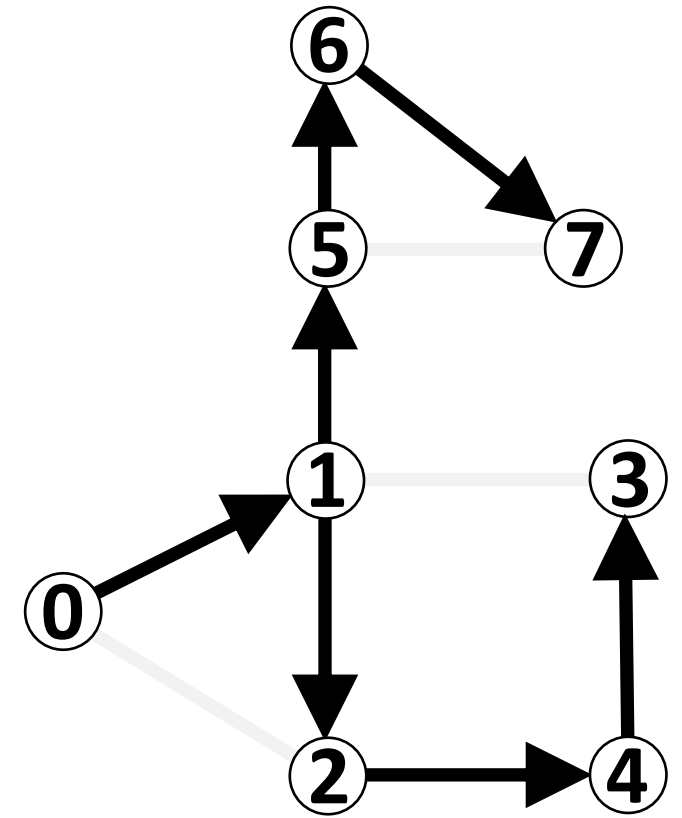
How do we determine the path from 0 to 3?

Graphs - Paths

`int[] previousVertex`



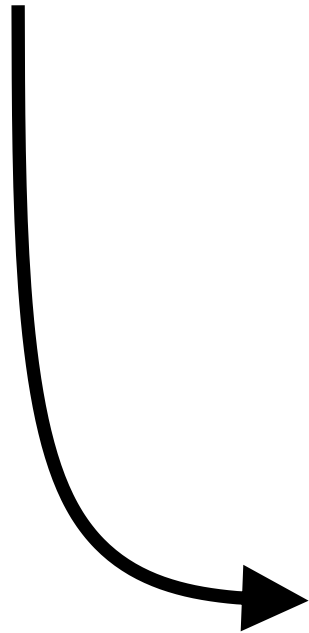
0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6



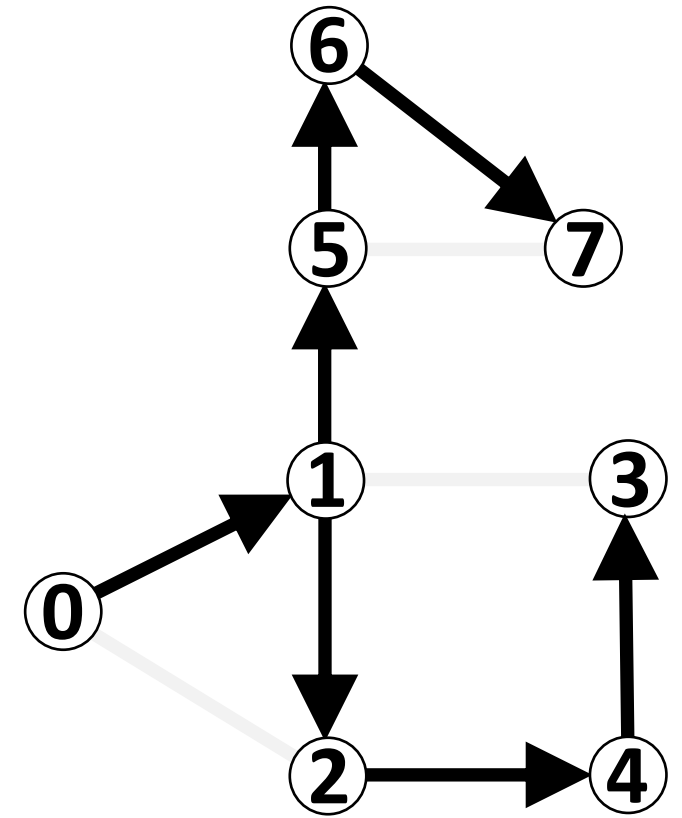
How do we determine the path from 0 to 3?

Graphs - Paths

`int[] previousVertex`



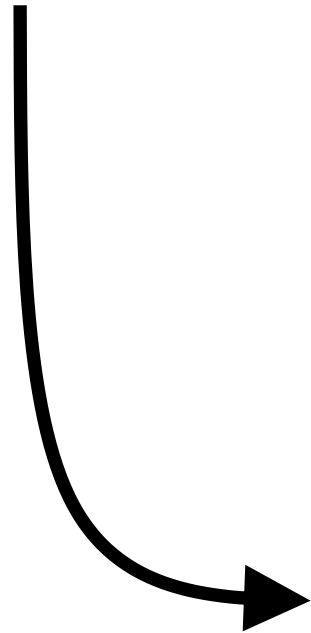
0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6



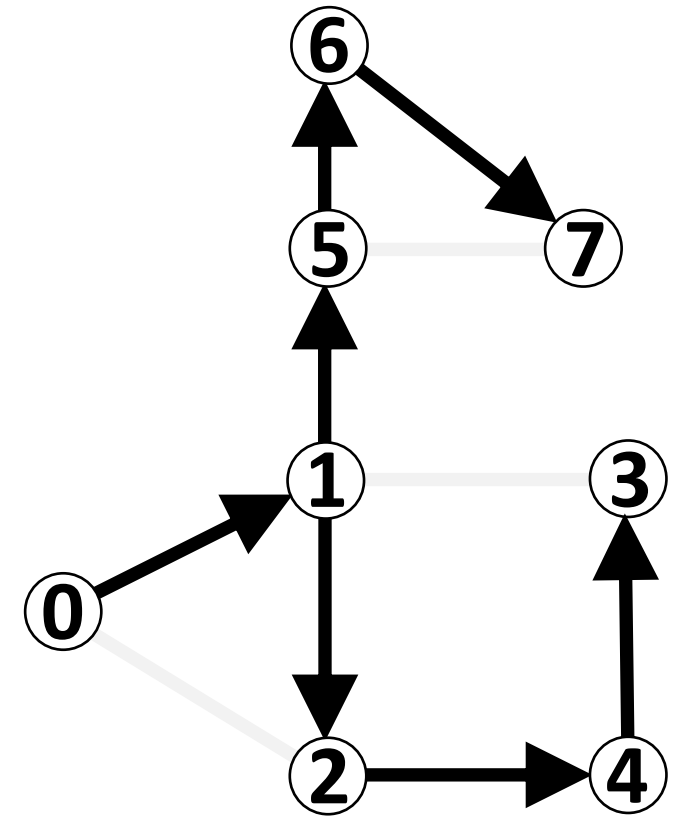
How do we determine the path from 0 to 3?

Graphs - Paths

`int[] previousVertex`



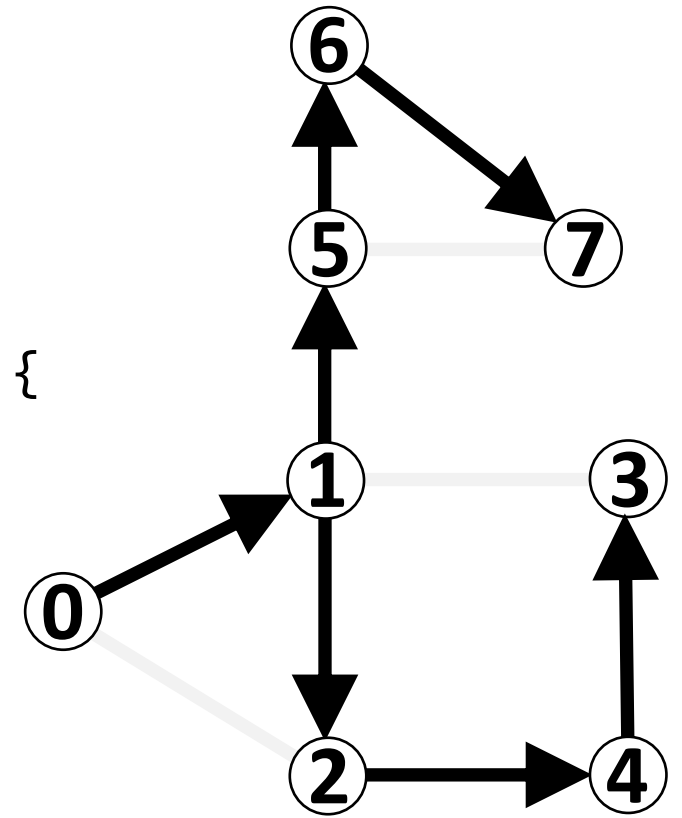
0	-
1	0
2	1
3	4
4	2
5	1
6	5
7	6



How do we determine the path from 0 to 3?

Graphs - Paths

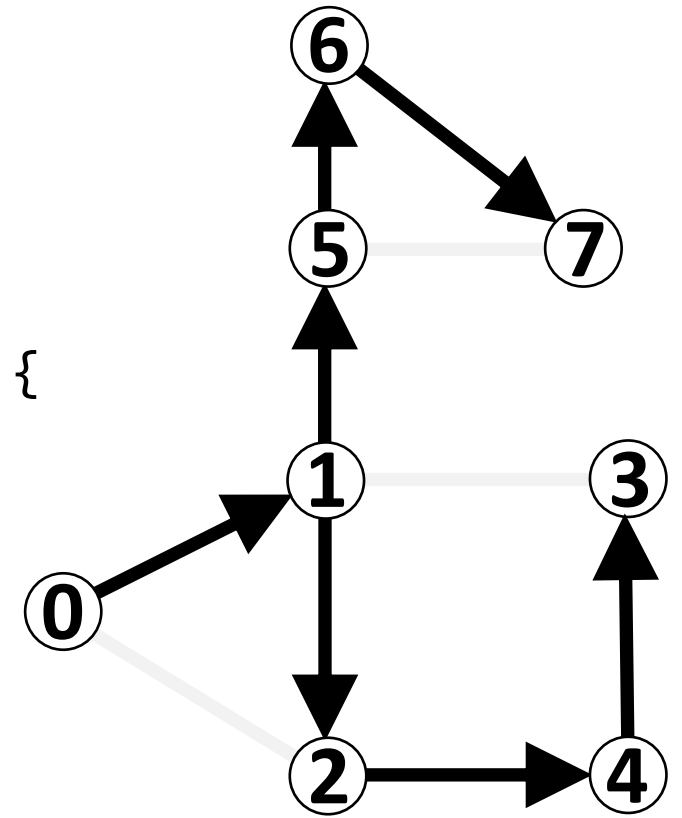
```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```



What do we need to do in the code?

Graphs - Paths

```
private boolean[] visited;  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
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    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

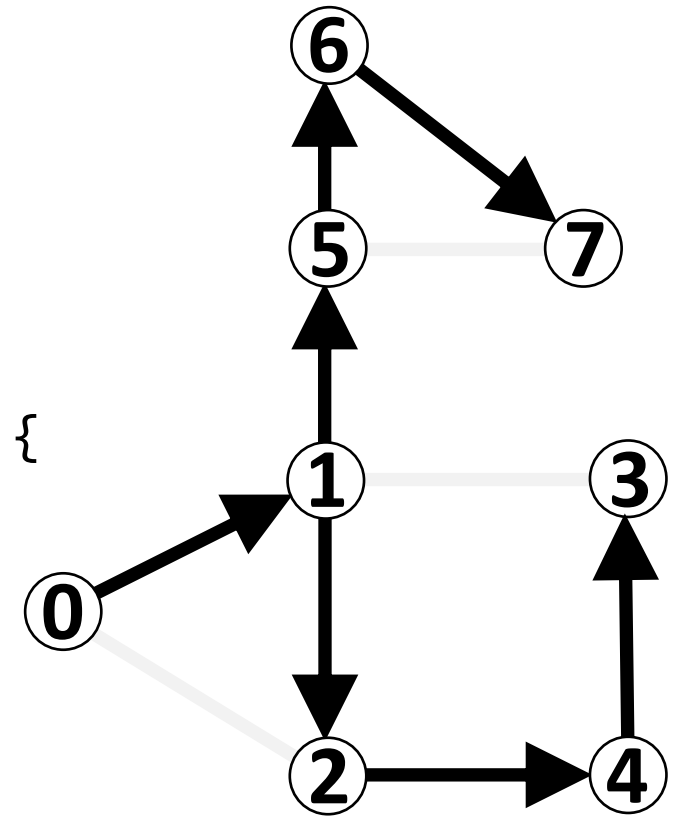


What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
private boolean[] visited;  
private int[] previousVertex;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    previousVertex = new int[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            dfs(graph, neighbor);  
        }  
    }  
}
```

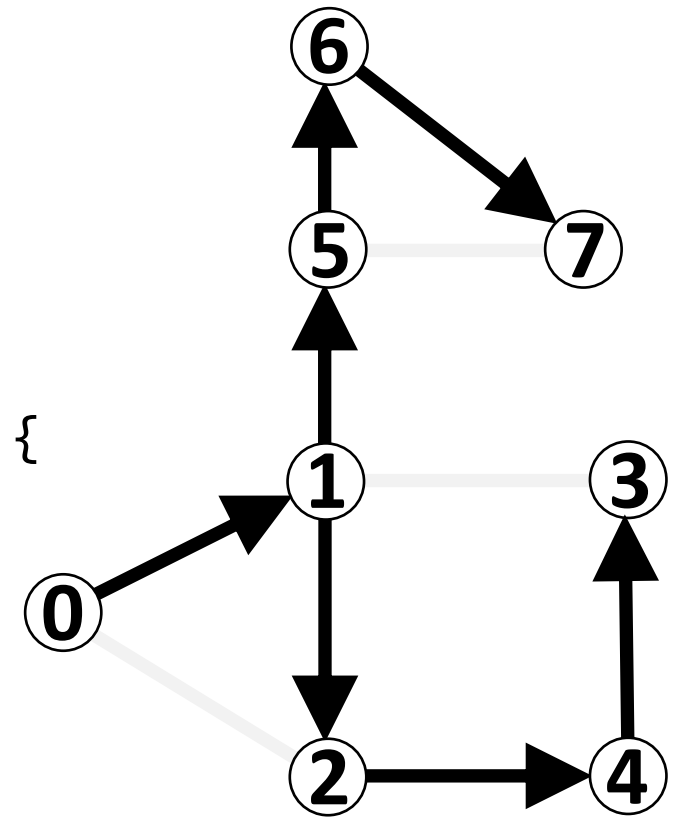


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- 1 – Create/Initialize previousVertex**
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- 3 – getPathTo(int endVertex)**

Graphs - Paths

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private boolean[] visited;  
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    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            previousVertex[?????] = ?????;  
            dfs(graph, neighbor);  
        }  
    }  
}
```

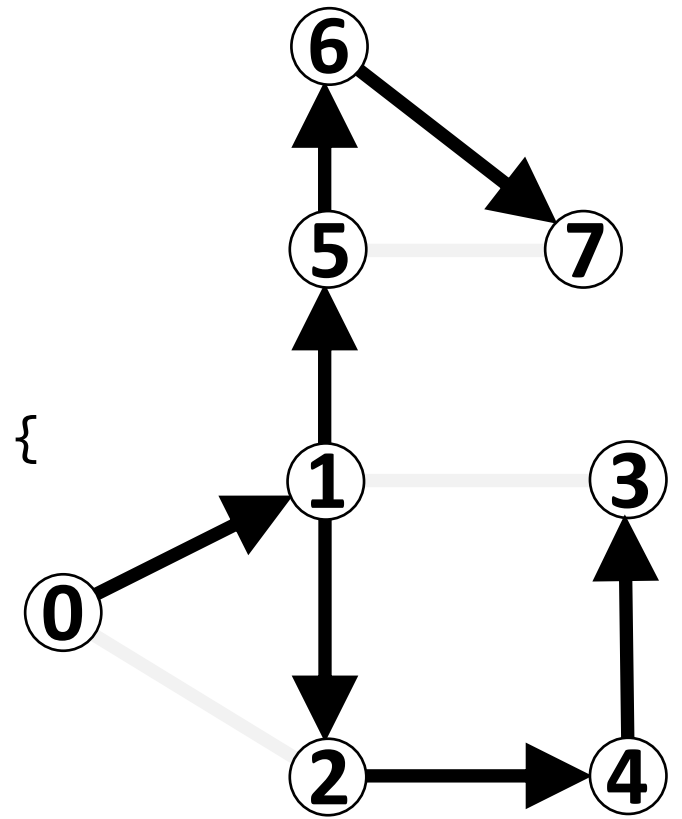


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- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

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    previousVertex = new int[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            previousVertex[vertex] = neighbor;  
            dfs(graph, neighbor);  
        }  
    }  
}
```

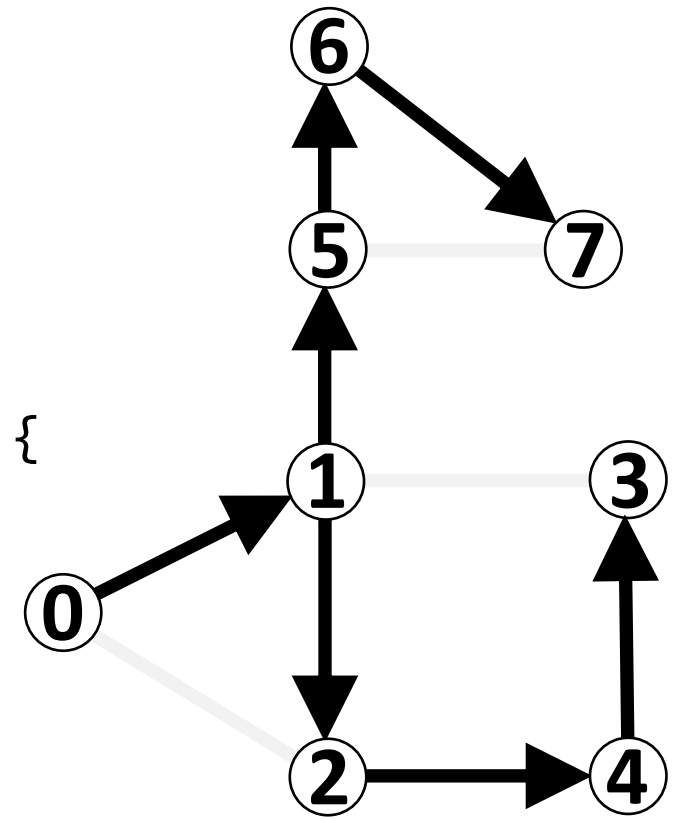


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Graphs - Paths

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    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            previousVertex[neighbor] = vertex;  
            dfs(graph, neighbor);  
        }  
    }  
}
```



What do we need to do in the code?

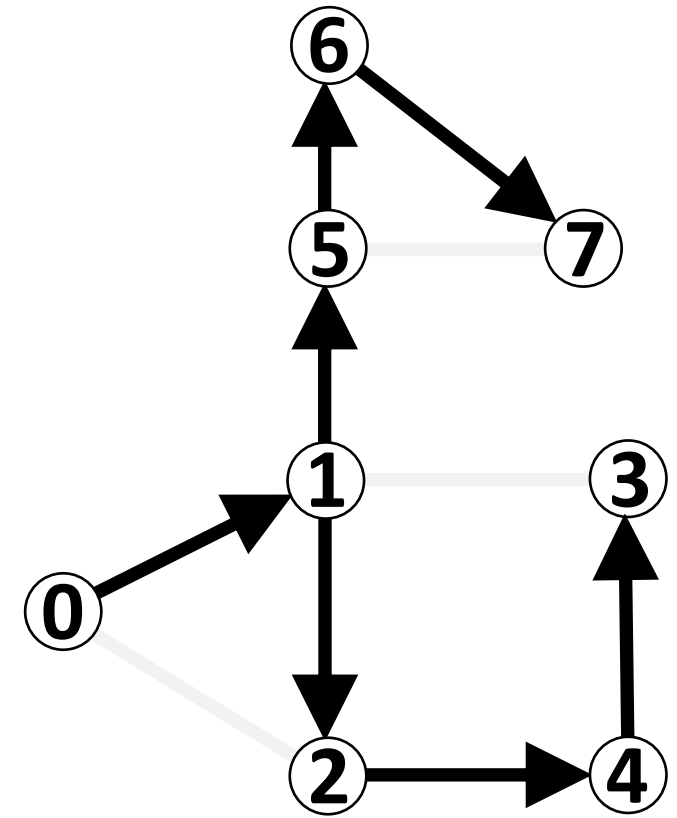
- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

public

???

getPathTo(int endVertex) {



What do we need to do in the code?

1 – Create/Initialize previousVertex

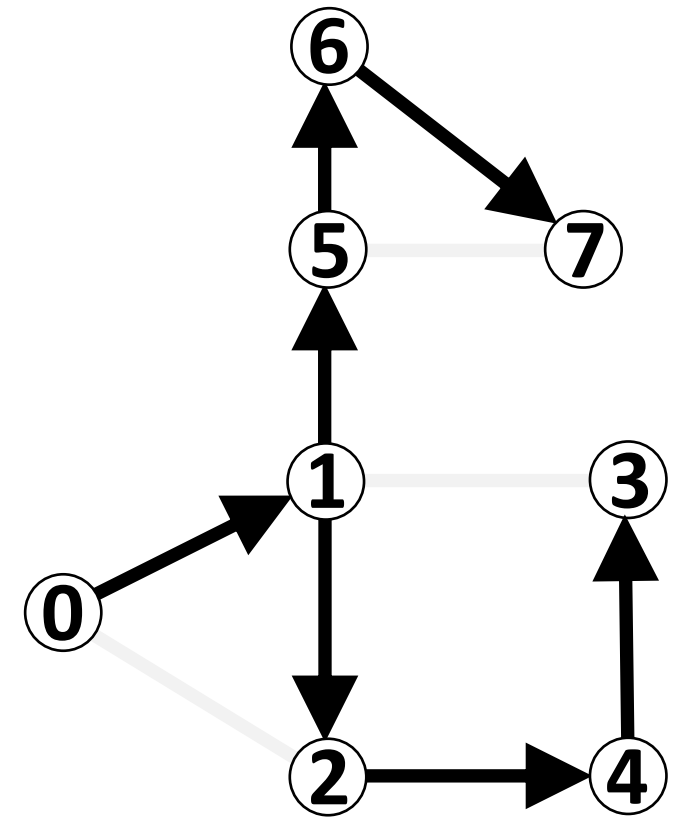
2 – Populate previousVertex

3 – getPathTo(int endVertex)

}

Graphs - Paths

```
public      ???      getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
    } else {  
  
    }  
}
```

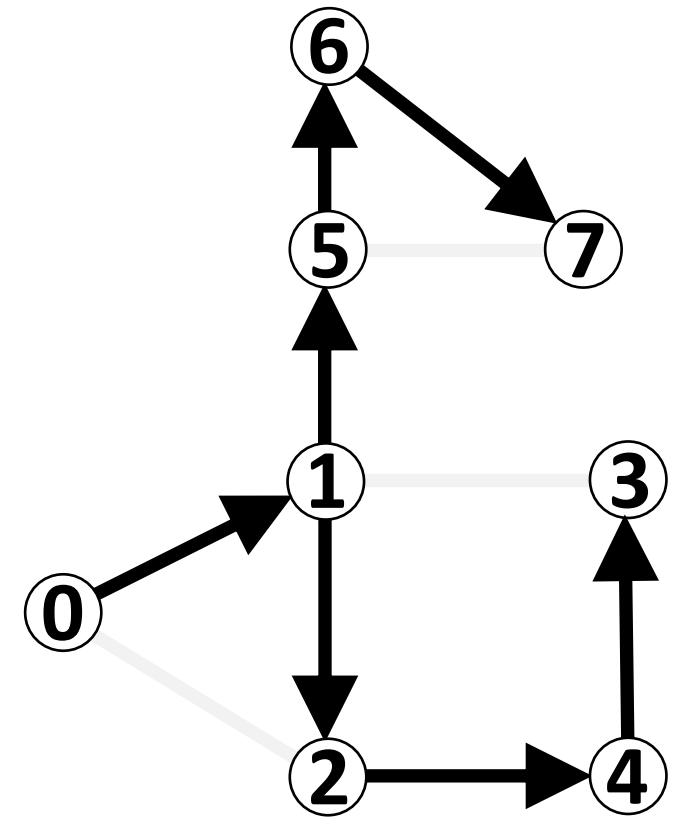


What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
public      ???      getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
  
    }  
}
```

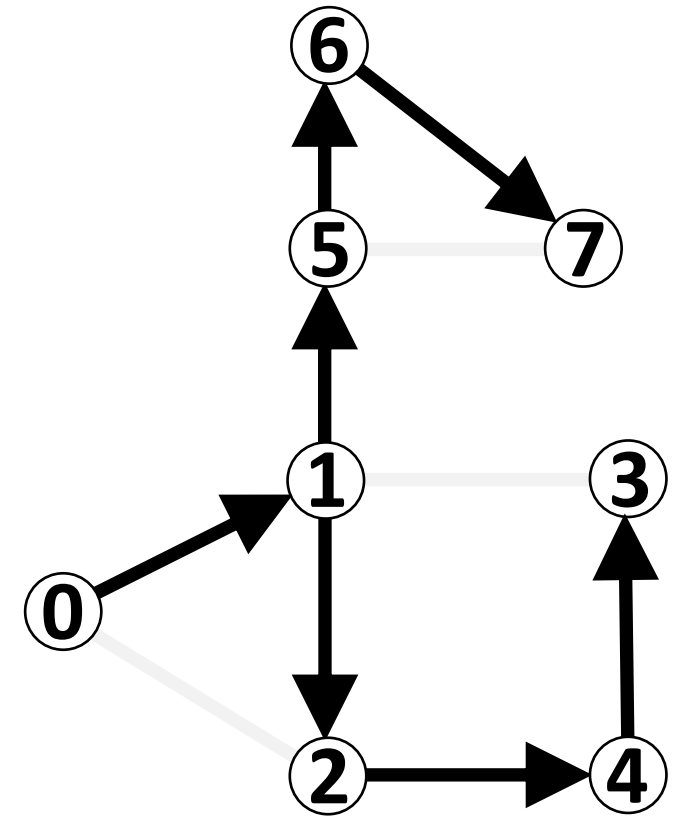


What do we need to do in the code?

- 1 – Create/Initialize previousVertex
- 2 – Populate previousVertex
- 3 – getPathTo(int endVertex)

Graphs - Paths

```
public      ???      getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        ??      path = ??  
    }  
}
```

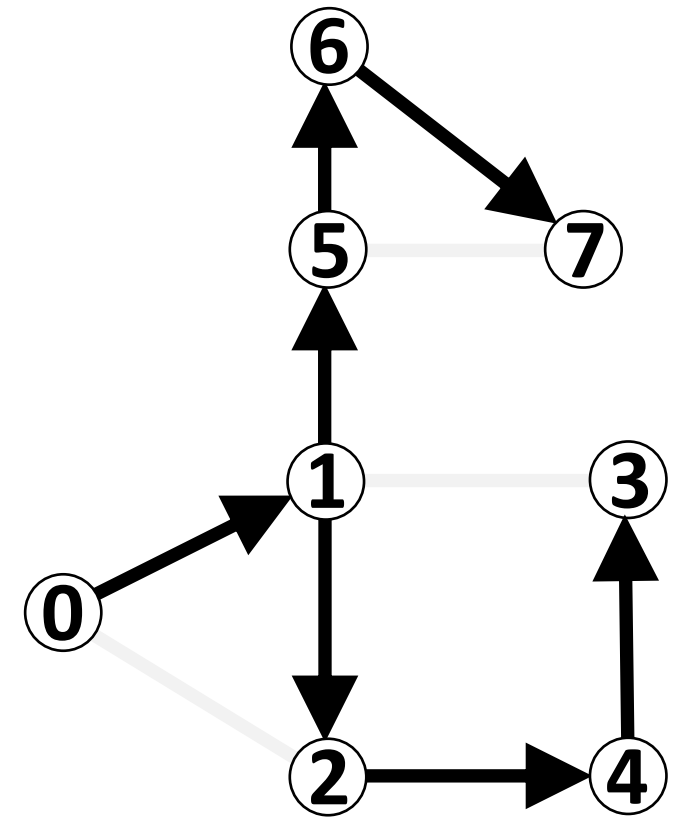


What do we need to do in the code?

- 1 – Create/Initialize previousVertex
- 2 – Populate previousVertex
- 3 – getPathTo(int endVertex)

Graphs - Paths

```
public      ???      getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
  
    }  
}
```



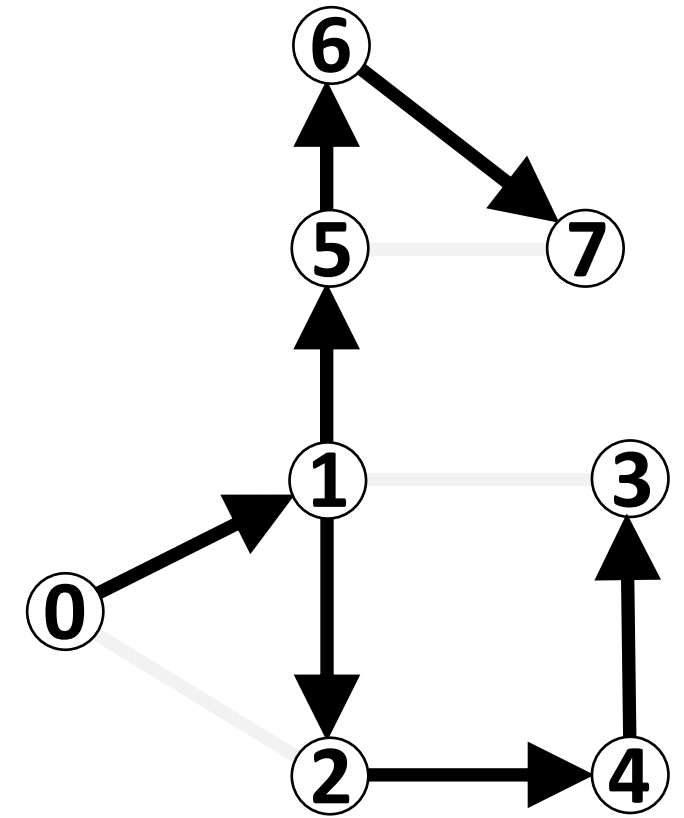
What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  

```



What do we need to do in the code?

1 – Create/Initialize previousVertex

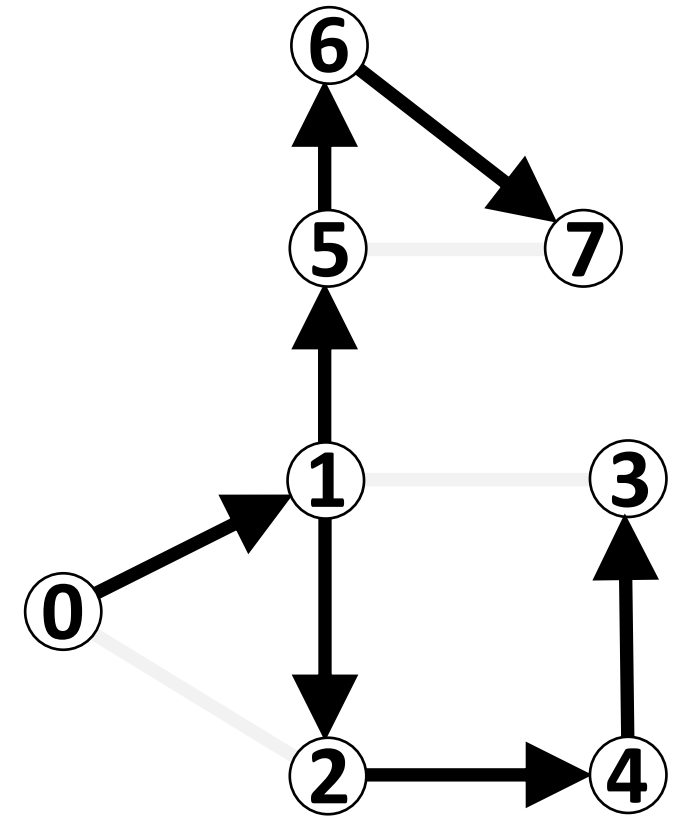
2 – Populate previousVertex

3 – getPathTo(int endVertex)

```
}  
}
```

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = ?? ; ; ) {  
  
        }  
    }  
}
```

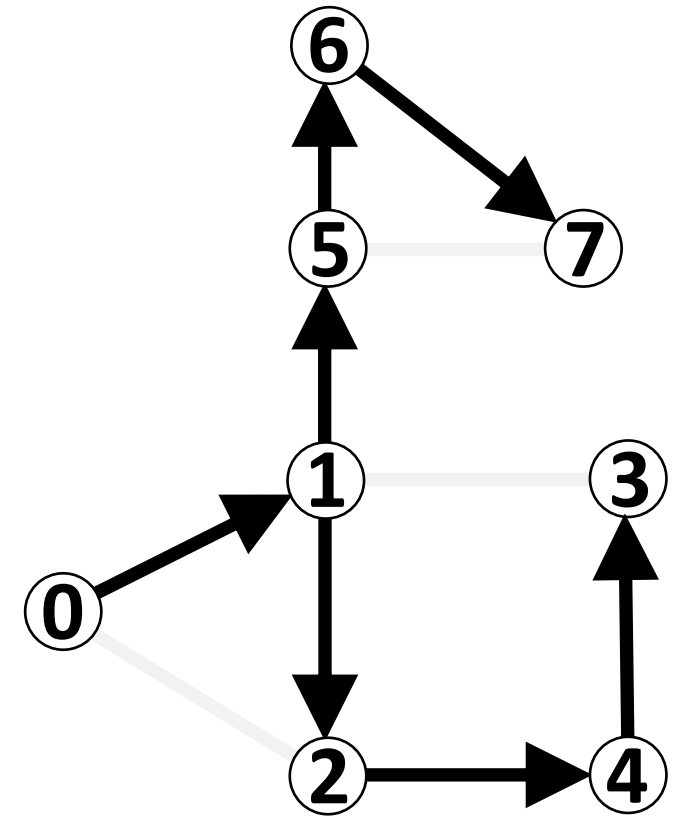


What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v ?? ; ) {  
  
        }  
    }  
}
```

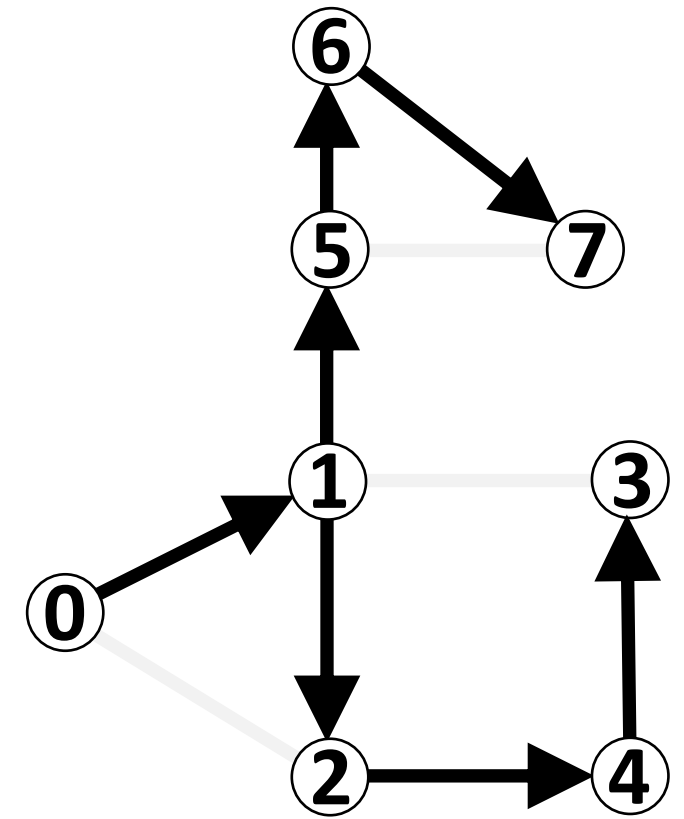


What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v != startVertex;  
            ) {  
            }  
        }  
    }  
}
```

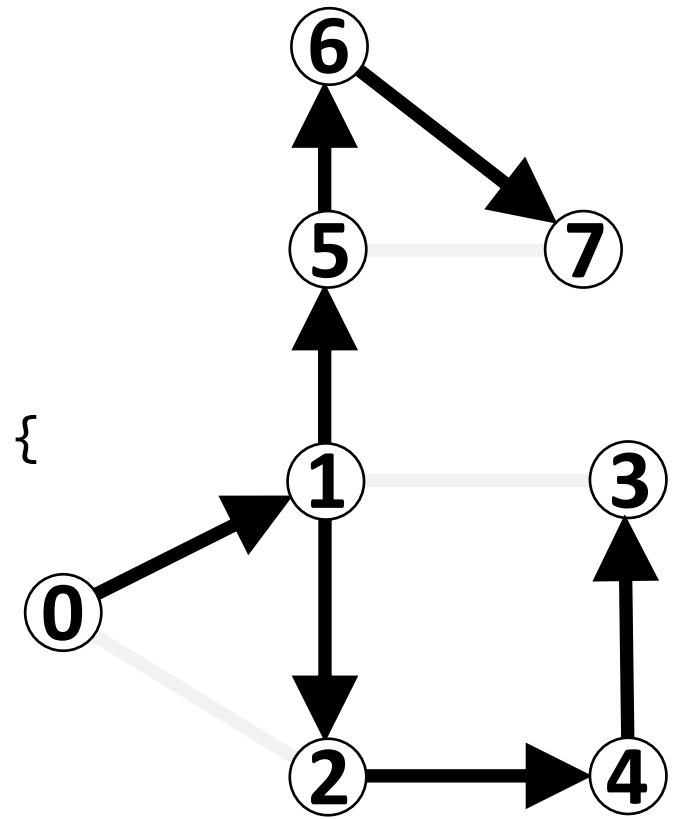


What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
private boolean[] visited;  
private int[] previousVertex;  
  
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    previousVertex = new int[graph.getNumVertices()];  
    dfs(graph, startVertex);  
}  
  
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            previousVertex[neighbor] = vertex;  
            dfs(graph, neighbor);  
        }  
    }  
}
```



What do we need to do in the code?

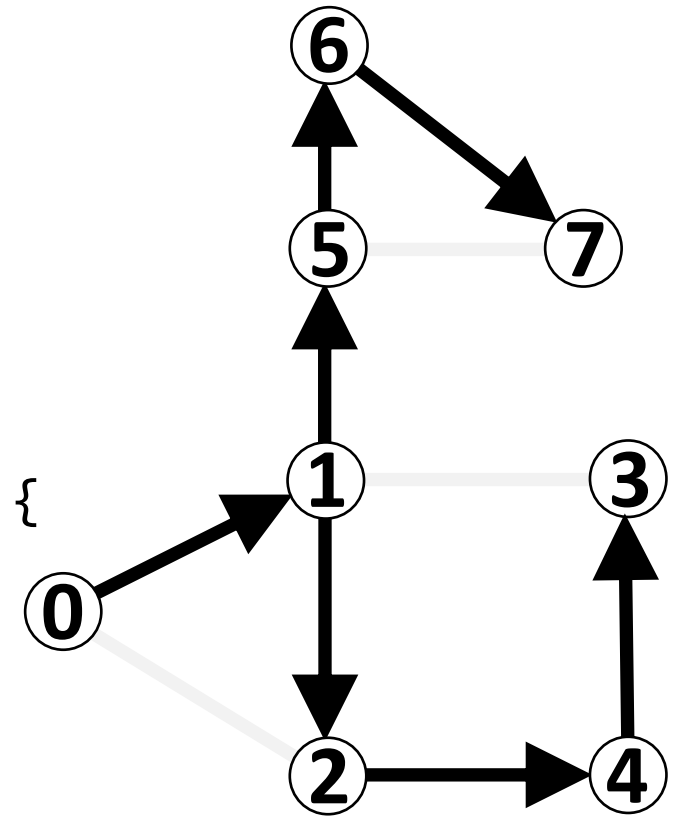
- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
private boolean[] visited;  
private int[] previousVertex;  
private int startVertex;
```

```
public DepthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    previousVertex = new int[graph.getNumVertices()];  
    this.startVertex = startVertex;  
    dfs(graph, startVertex);  
}
```

```
private void dfs(Graph graph, int vertex) {  
    visited[vertex] = true;  
    for (int neighbor : graph.getNeighbors(vertex)) {  
        if (!visited[neighbor]) {  
            previousVertex[neighbor] = vertex;  
            dfs(graph, neighbor);  
        }  
    }  
}
```

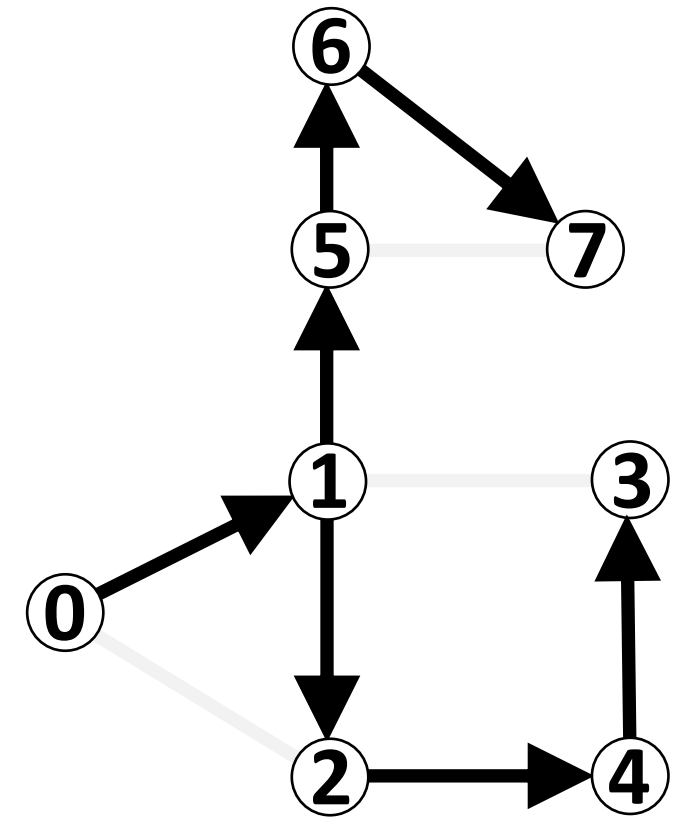


What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v != startVertex;  
            ) {  
            }  
        }  
    }  
}
```



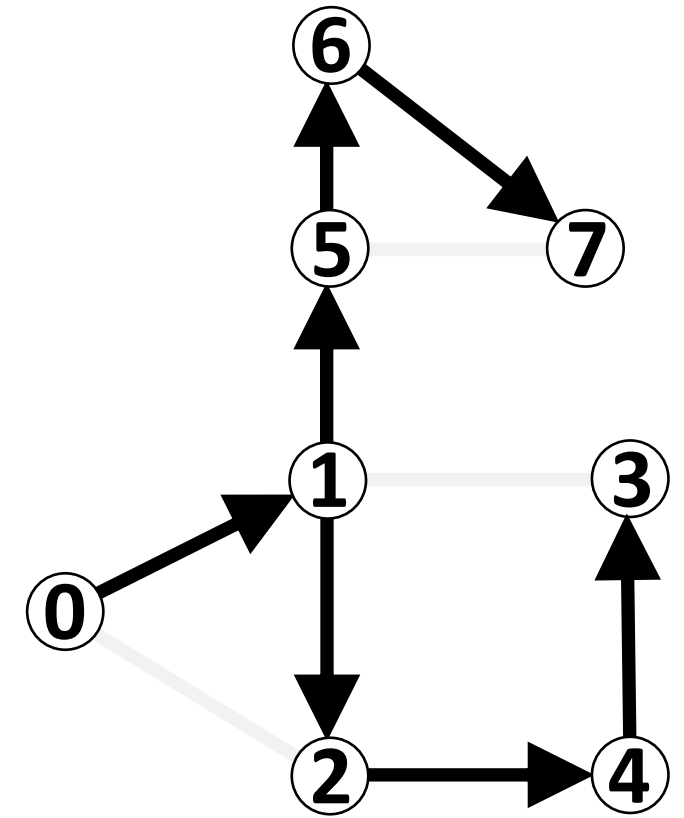
What do we need to do in the code?

- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Paths

```
private int[] previousVertex;
```

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v != startVertex; v ??  
    }  
}
```



What do we need to do in the code?

1 – Create/Initialize previousVertex

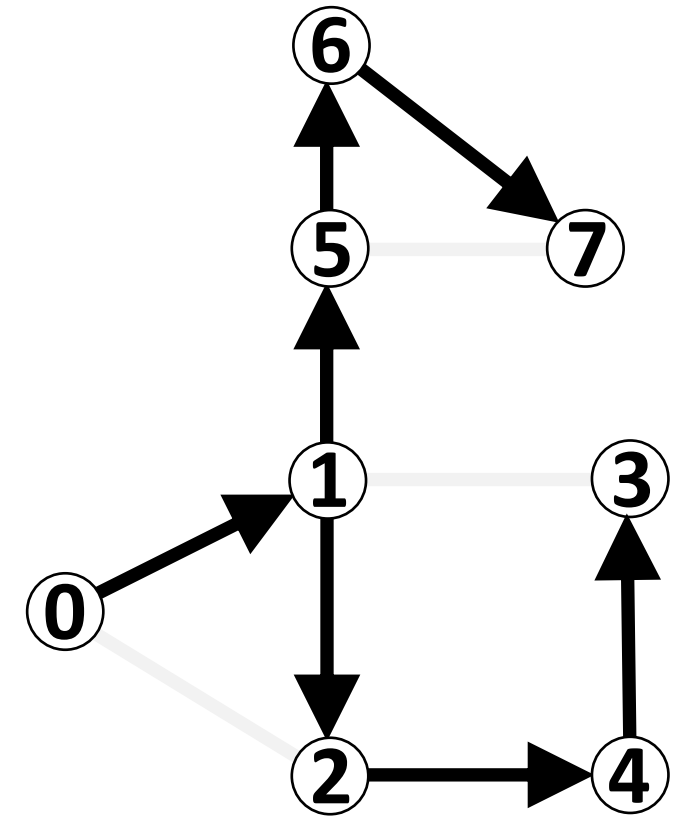
2 – Populate previousVertex

3 – getPathTo(int endVertex)

Graphs - Paths

```
private int[] previousVertex;
```

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v != startVertex; v = previousVertex[v]) {  
  
        }  
    }  
}
```



What do we need to do in the code?

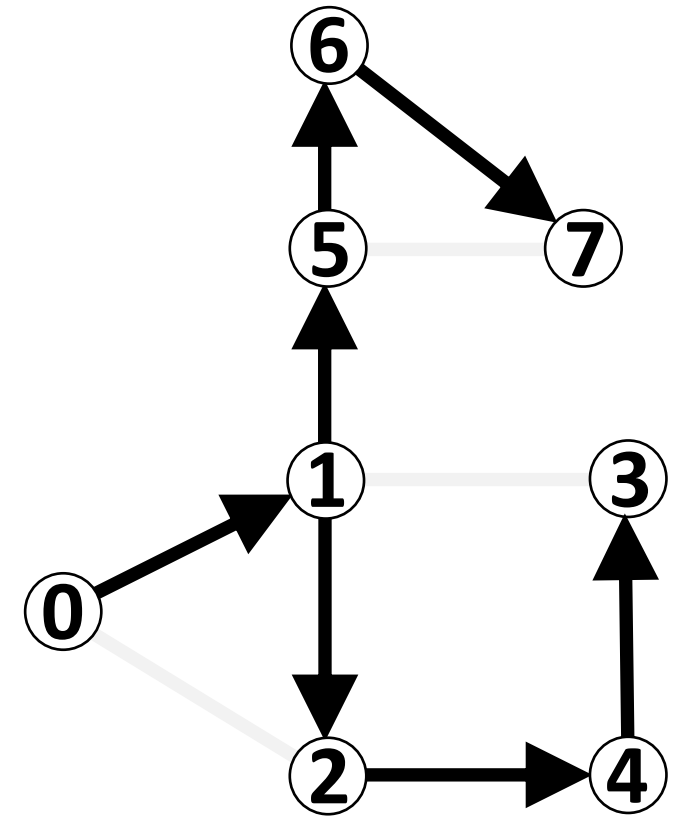
1 – Create/Initialize previousVertex

2 – Populate previousVertex

3 – getPathTo(int endVertex)

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v != startVertex; v = previousVertex[v]) {  
            path.add(v);  
        }  
    }  
}
```



What do we need to do in the code?

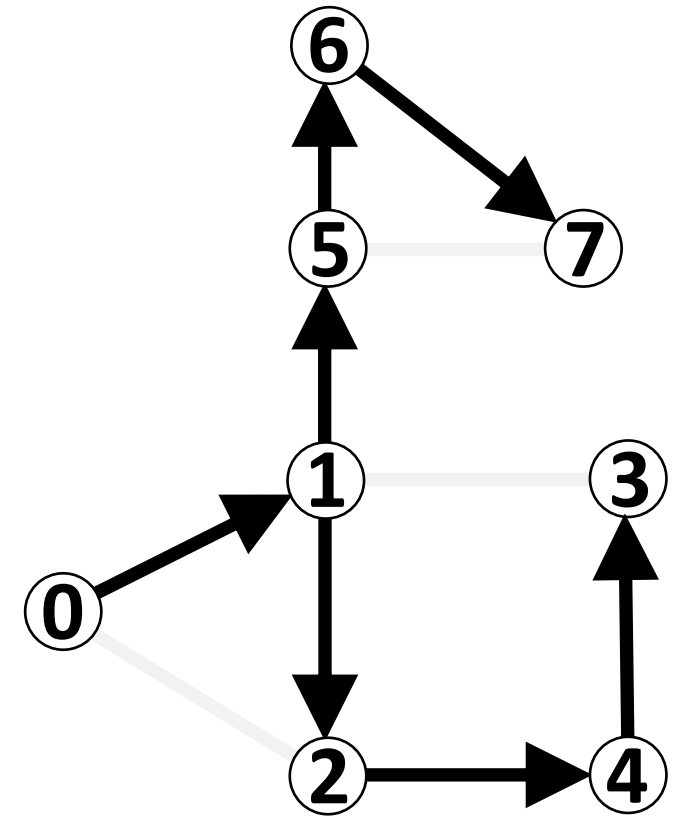
1 – Create/Initialize previousVertex

2 – Populate previousVertex

3 – getPathTo(int endVertex)

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v != startVertex; v = previousVertex[v]) {  
            path.addFirst(v);  
        }  
    }  
}
```



What do we need to do in the code?

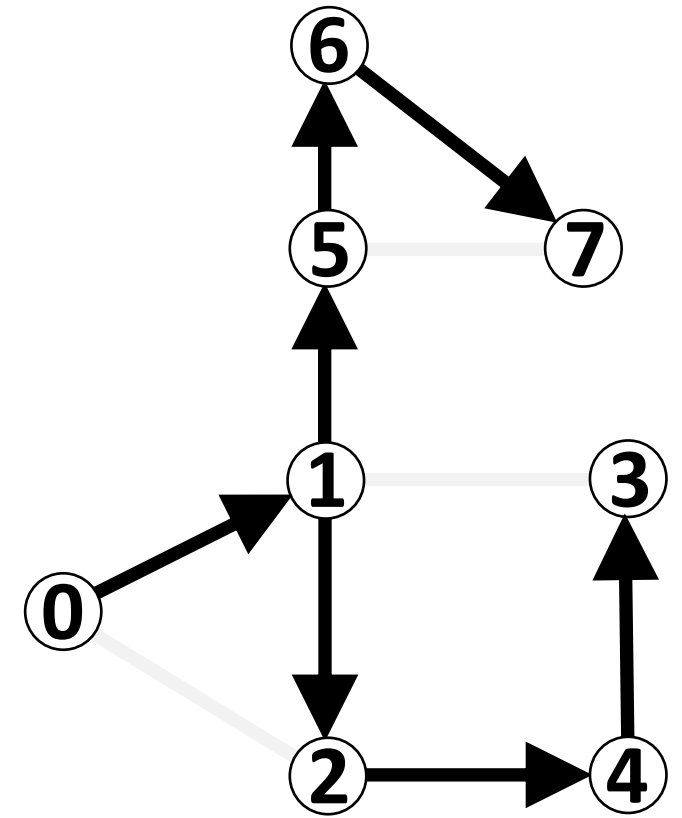
1 – Create/Initialize previousVertex

2 – Populate previousVertex

3 – getPathTo(int endVertex)

Graphs - Paths

```
public LinkedList<Integer> getPathTo(int endVertex) {  
    if (!reachable(endVertex)) {  
        return null;  
    } else {  
        LinkedList<Integer> path = new LinkedList<>();  
        for (int v = endVertex; v != startVertex; v = previousVertex[v]) {  
            path.addFirst(v);  
        }  
        path.addFirst(startVertex);  
        return path;  
    }  
}
```

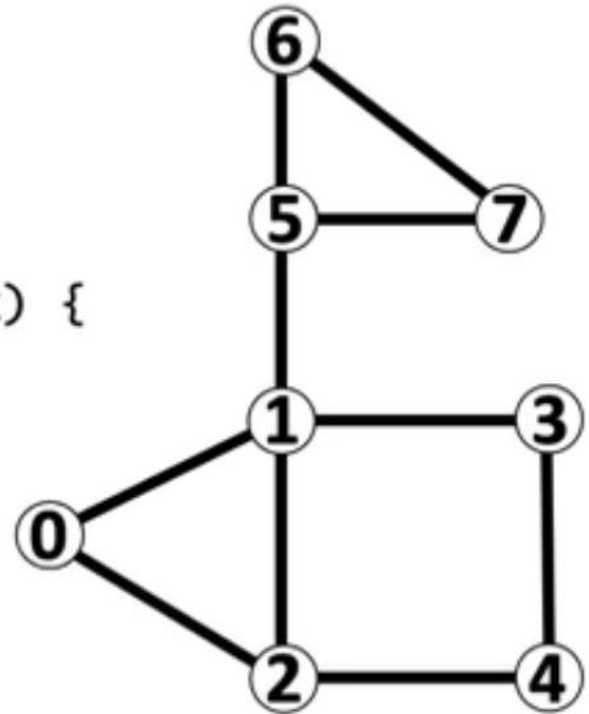


What do we need to do in the code?

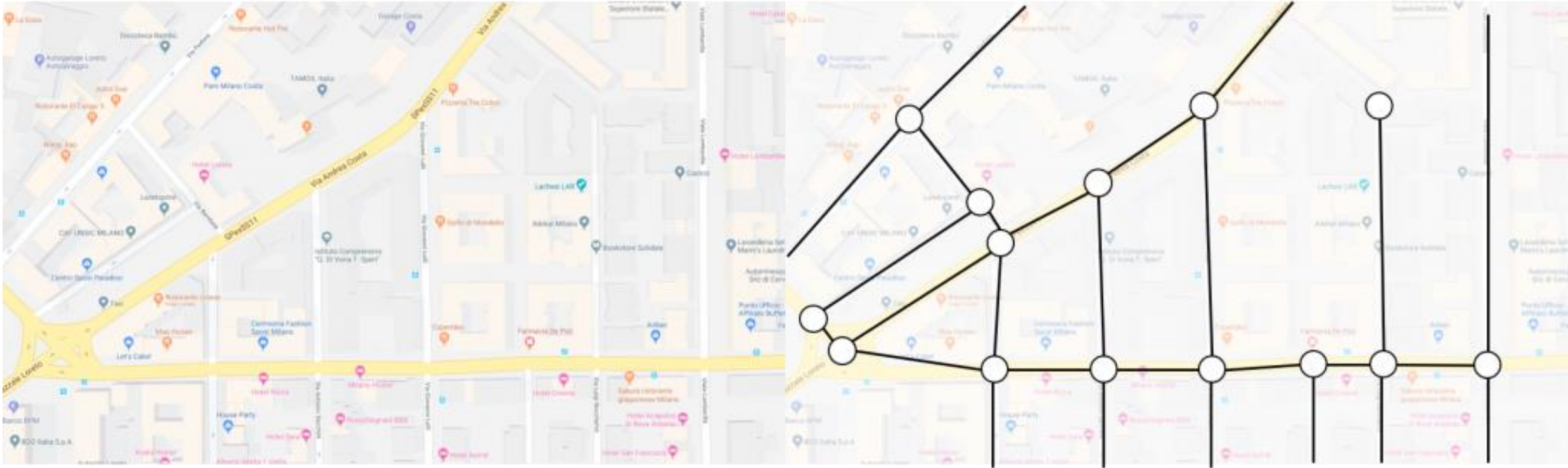
- 1 – Create/Initialize previousVertex**
- 2 – Populate previousVertex**
- 3 – getPathTo(int endVertex)**

Graphs - Breadth First Search

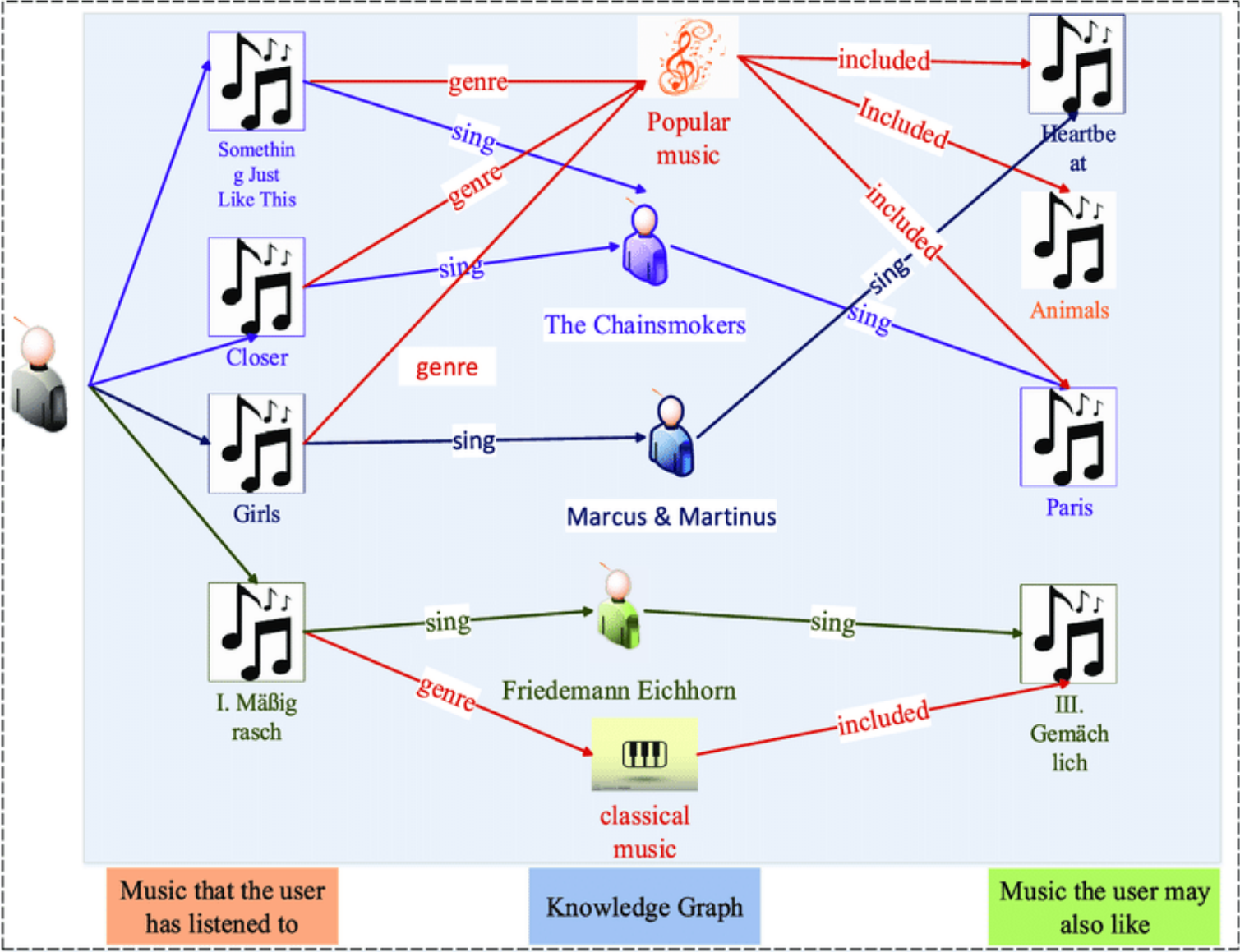
```
private boolean[] visited;  
public BreadthFirstSearch(Graph graph, int startVertex) {  
    visited = new boolean[graph.getNumVertices()];  
    bfs(graph, startVertex);  
}  
private void bfs(Graph graph, int startVertex) {  
    Queue<Integer> queue = new Queue<>();  
    visited[startVertex] = true;  
    queue.enqueue(startVertex);  
    while (!queue.isEmpty()) {  
        int vertex = queue.dequeue();  
        for (int neighbor : graph.getNeighbors(vertex)) {  
            if (!visited[neighbor]) {  
                visited[neighbor] = true;  
                queue.enqueue(neighbor);  
            }  
        }  
    }  
}
```



Graphs – More Applications



Graphs – More Applications



Graphs – More Applications

Montana State University

 23 languages 

Article [Talk](#)

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From Wikipedia, the free encyclopedia

Coordinates:  45°40′06″N 111°03′00″W

*"Montana State" redirects here. For the U.S. state, see [Montana](#).
This article is about the main campus in Bozeman. For other campuses, see [Montana State University \(disambiguation\)](#).*

Montana State University (MSU) is a [public land-grant research university](#) in [Bozeman](#), [Montana](#). It is the state's largest university.^[5] MSU offers baccalaureate degrees in 60 fields, master's degrees in 68 fields, and doctoral degrees in 35 fields through its nine colleges. More than 16,700 students attended MSU in the fall 2019, taught by 796 full-time and 547 part-time faculty.^[3] In the [Carnegie Classification](#), MSU is placed among "R1: Doctoral Universities – Very high research activity", one of only two universities to receive this distinction with a "very high undergraduate" enrollment profile.^{[6][7]} The university had research expenditures of \$129.6 million in 2017.^{[8][9]}

Located on the south side of [Bozeman](#), the university's 1,170 acres (470 ha) campus is the largest in the state. The university's main campus in Bozeman is home to [KUSM](#) television, [KGLT](#) radio, and the [Museum of the Rockies](#). MSU provides outreach services to citizens and communities statewide through its agricultural experiment station and 60 county and reservation extension offices. The elevation of the campus is 4,900 feet (1,500 m) [above sea level](#).^[10]

History [\[edit \]](#)

Montana State University



Former name	Agricultural College of the State of Montana (1893–1913) Montana College of Agriculture and Mechanic Arts (1913–1965)
Motto	"Mountains & Minds"
Type	Public land-grant research

Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Graphs – More Applications

1

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

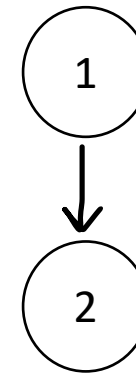
Handwritten annotation: A large closing curly brace '}' is placed to the right of the initialization lines 'low = 0;' and 'high = n - 1;', with a subscript '1' written next to it.

Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Handwritten annotations: A bracket labeled '1' groups the initialization of low and high. A bracket labeled '2' groups the while loop condition and the loop body.



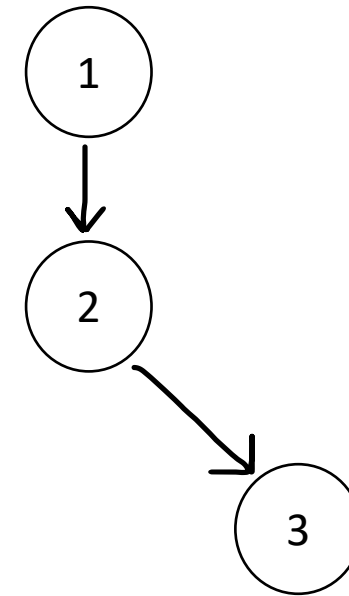
Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Handwritten annotations on the code:

- A bracket labeled '1' groups the initialization of `low` and `high`.
- A bracket labeled '2' groups the `while` loop condition and its body.
- A bracket labeled '3' groups the `if-else` logic inside the `while` loop.



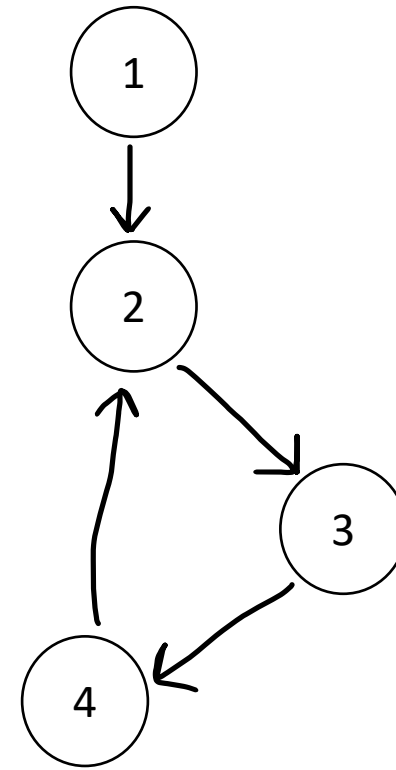
Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Handwritten annotations on the code:

- A bracket labeled '1' groups the initialization of `low` and `high`.
- A bracket labeled '2' groups the `while` loop condition.
- A bracket labeled '3' groups the calculation of `mid`.
- A bracket labeled '4' groups the `if` and `else if` statements.



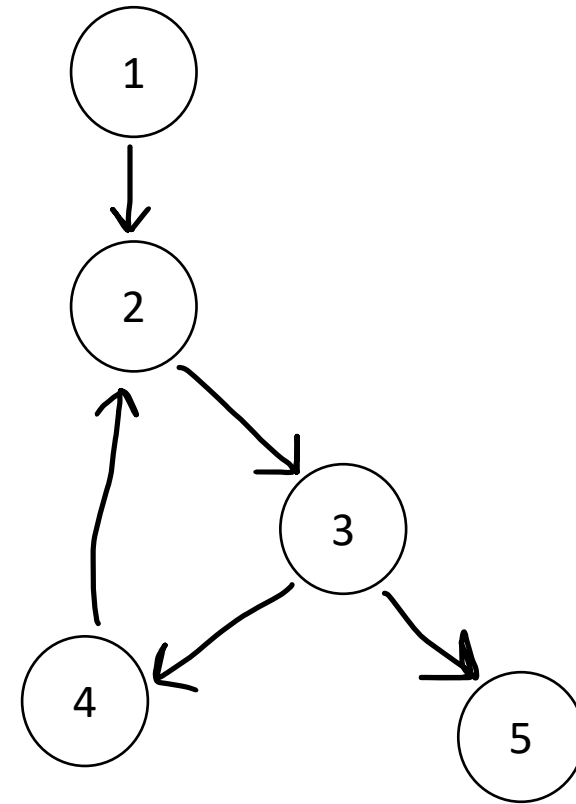
Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Handwritten annotations on the code:

- A bracket labeled '1' groups the initialization of `low` and `high`.
- A bracket labeled '2' groups the `while` loop condition.
- A bracket labeled '3' groups the calculation of `mid`.
- A bracket labeled '4' groups the `if` statement.
- A bracket labeled '5' groups the `else if` statement.



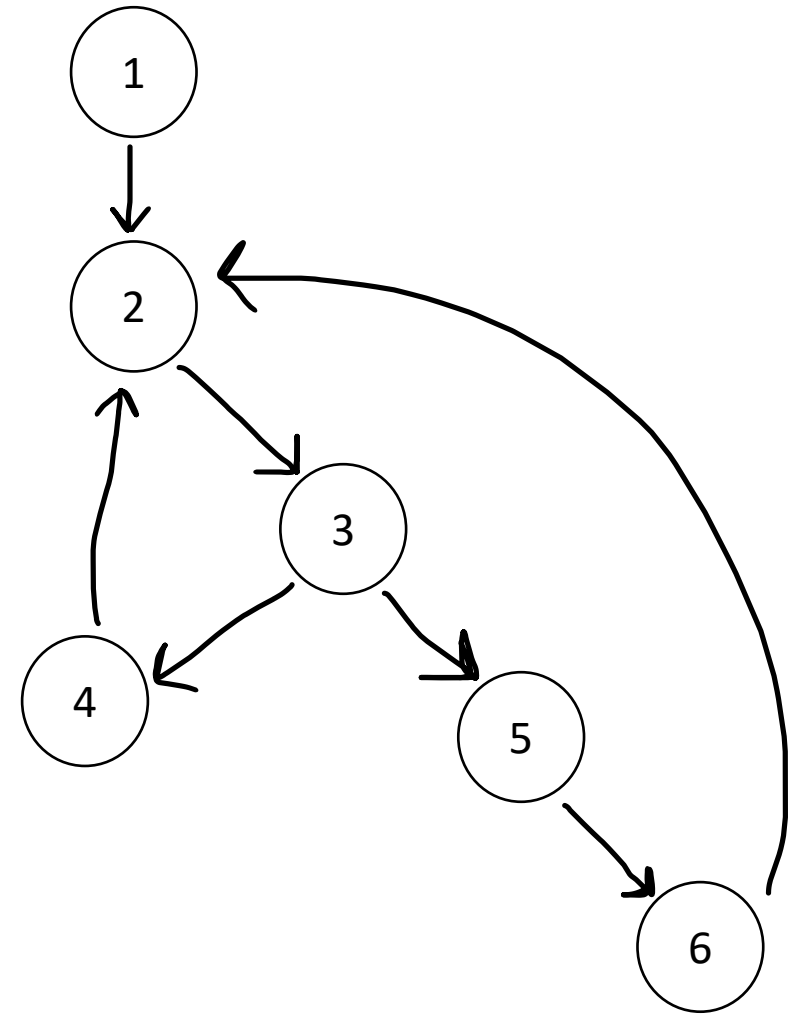
Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Handwritten annotations on the code:

- A bracket labeled '1' spans the initialization of `low` and `high`.
- A bracket labeled '2' spans the `while` loop condition.
- A bracket labeled '3' spans the calculation of `mid`.
- A bracket labeled '4' spans the `if` condition.
- A bracket labeled '5' spans the `else if` condition.
- A bracket labeled '6' spans the `else` branch.



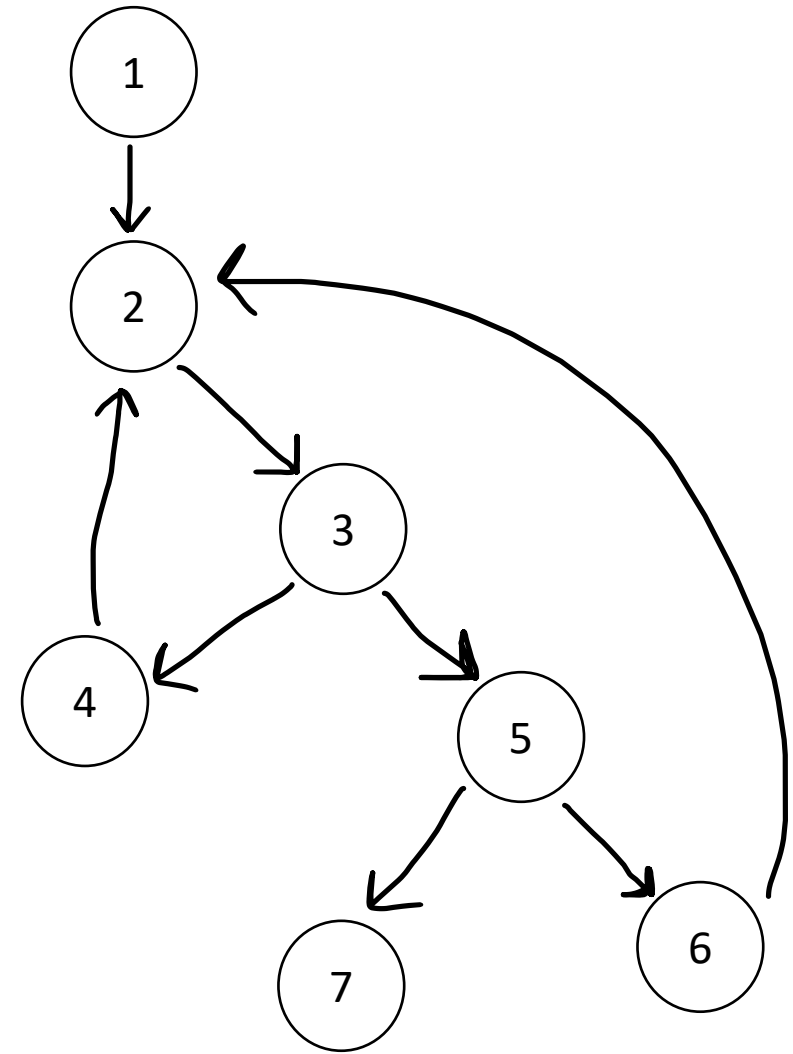
Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Handwritten annotations on the code:

- 1: Next to the closing brace of the `while` loop.
- 2: Next to the opening brace of the `while` loop.
- 3: Next to the assignment `mid = (low + high) / 2;`.
- 4: Next to the assignment `high = mid - 1;`.
- 5: Next to the assignment `low = mid + 1;`.
- 6: Next to the assignment `low = mid + 1;`.
- 7: Next to the `else return mid;` statement.



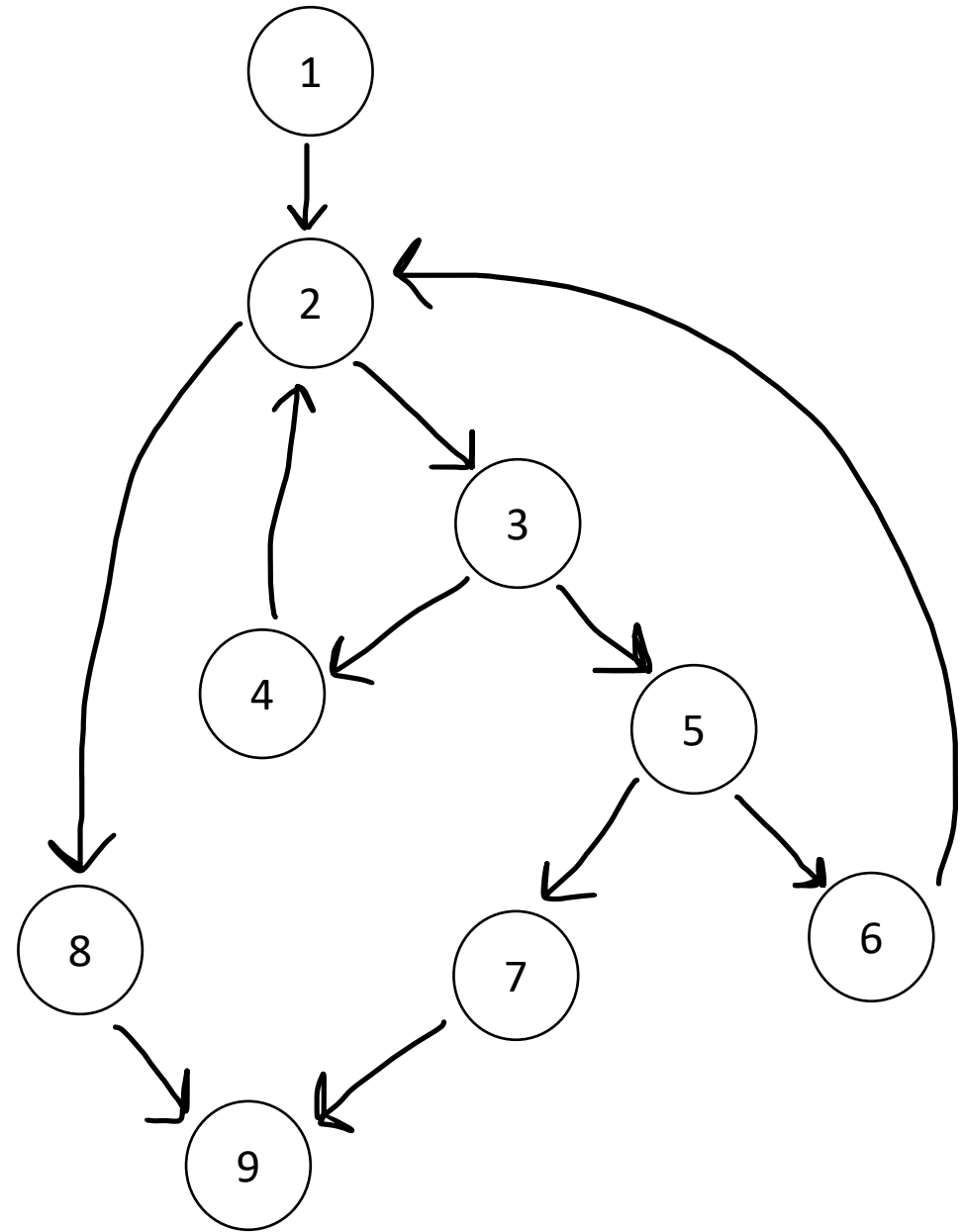
Graphs – More Applications

Source Program:

```
int binsearch(int x, int v[], int n)
{
    int low, high, mid;
    low = 0;
    high = n - 1;
    while (low <= high)
    {
        mid = (low + high) / 2;
        if (x < v[mid])
            high = mid - 1;
        else if (x > v[mid])
            low = mid + 1;
        else return mid;
    }
    return -1;
}
```

Handwritten annotations for line counting:

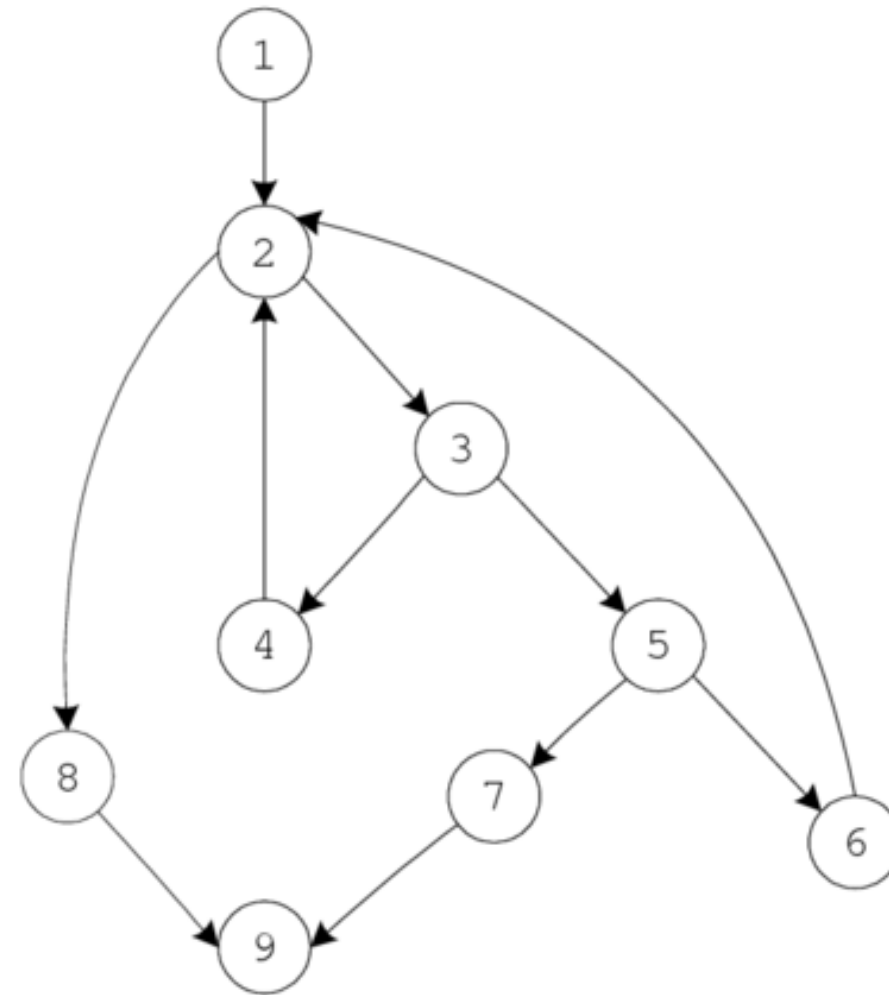
- Line 1: `int low, high, mid;`
- Line 2: `low = 0;`
- Line 3: `high = n - 1;`
- Line 4: `while (low <= high)`
- Line 5: `{`
- Line 6: `mid = (low + high) / 2;`
- Line 7: `if (x < v[mid])`
- Line 8: `high = mid - 1;`
- Line 9: `else if (x > v[mid])`
- Line 10: `low = mid + 1;`
- Line 11: `else return mid;`
- Line 12: `}`
- Line 13: `return -1;`
- Line 14: `}`



Source Program:

```
int binsearch(int x, int v[], int n)
{
    1 | int low, high, mid;
      | low = 0;
      | high = n - 1;
      | while (low <= high) | 2
      | {
          3 | mid = (low + high) / 2;
            | if (x < v[mid])
              |     high = mid - 1; | 4
          5 | else if (x > v[mid])
              |     low = mid + 1; | 6
          7 | else return mid;
            | }
      | return -1; | 8
    } | 9
```

CFG:



Control Flow Graph (CFG)

Identifying malware

