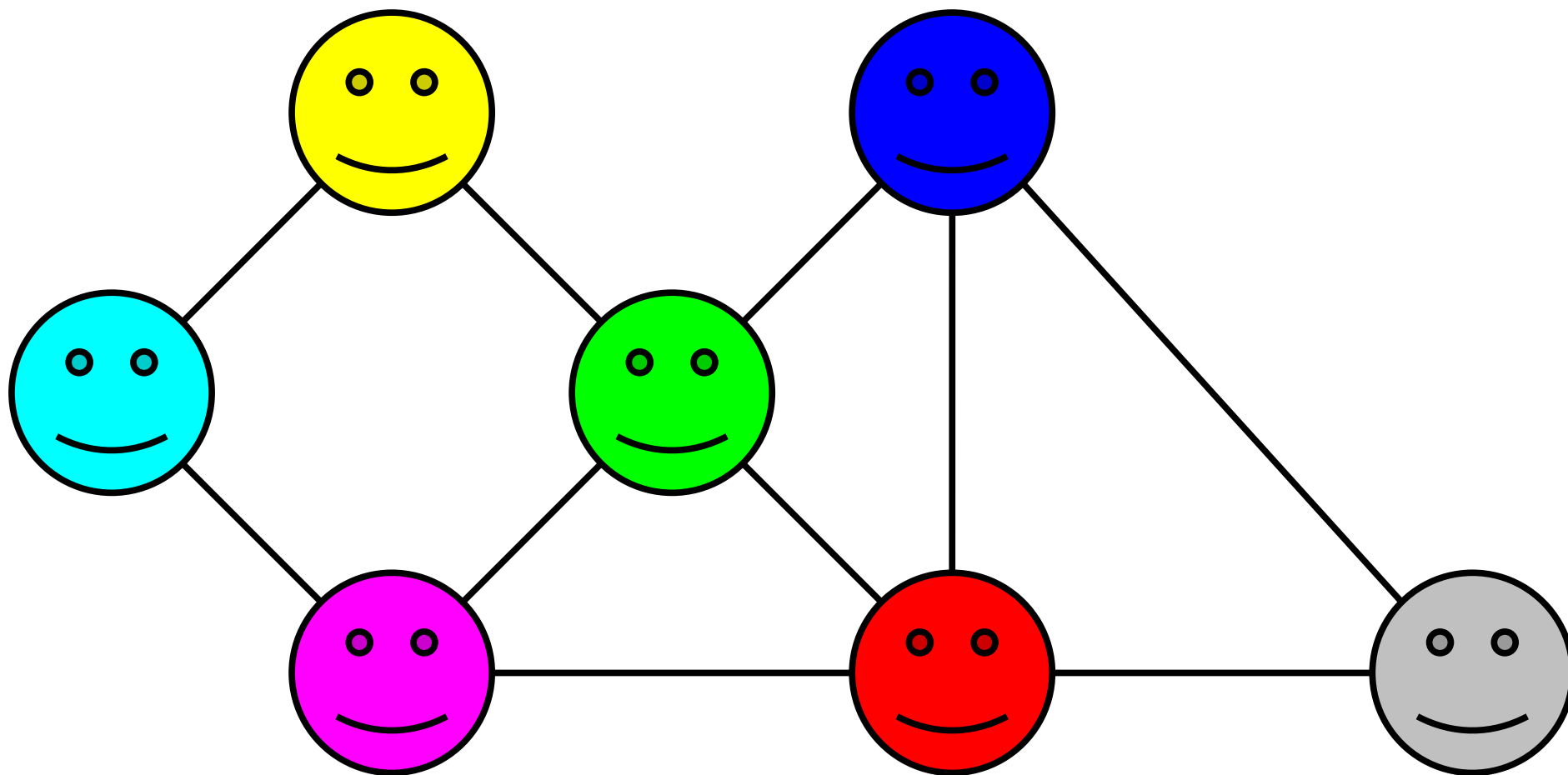
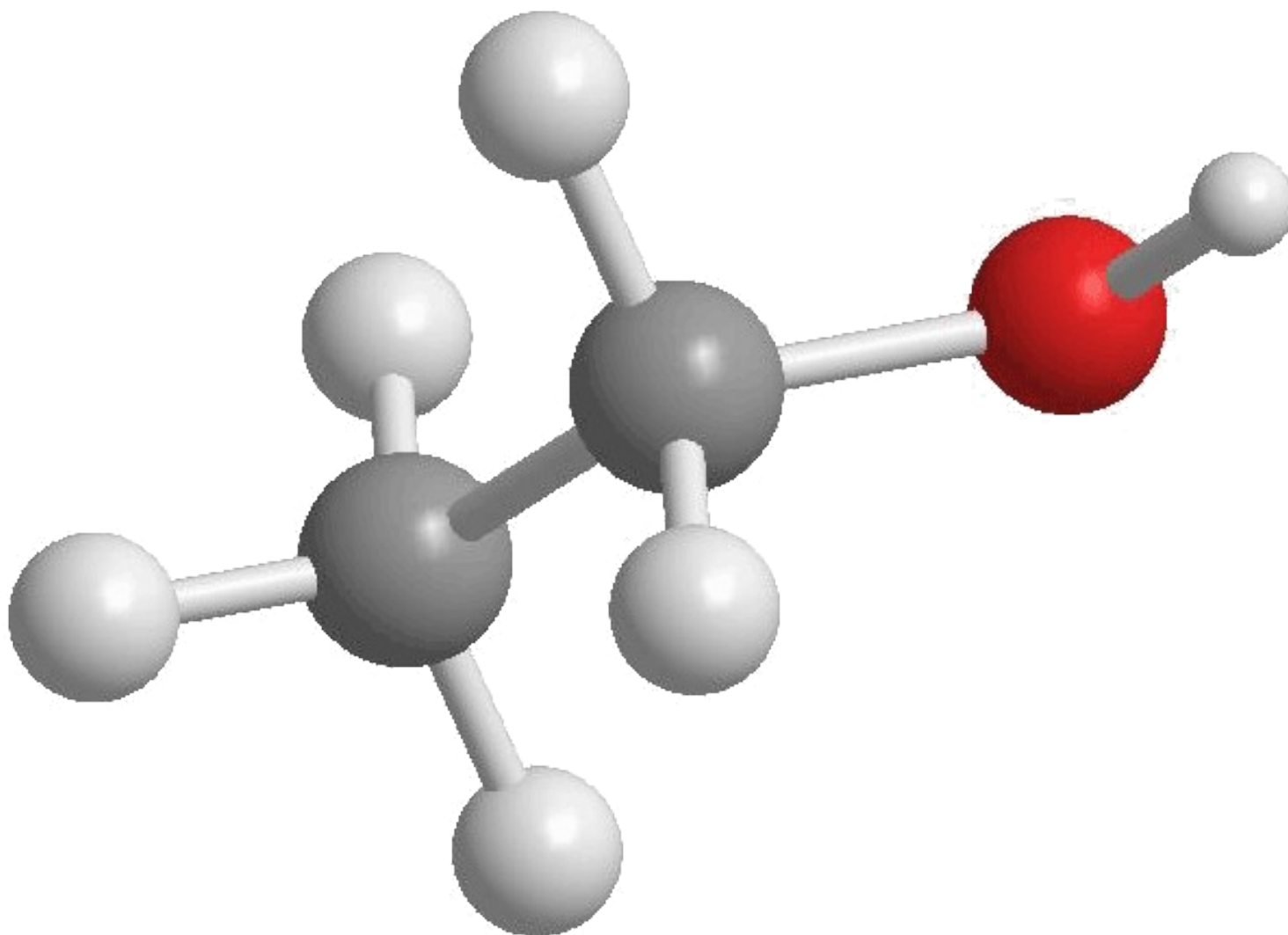


Graphs

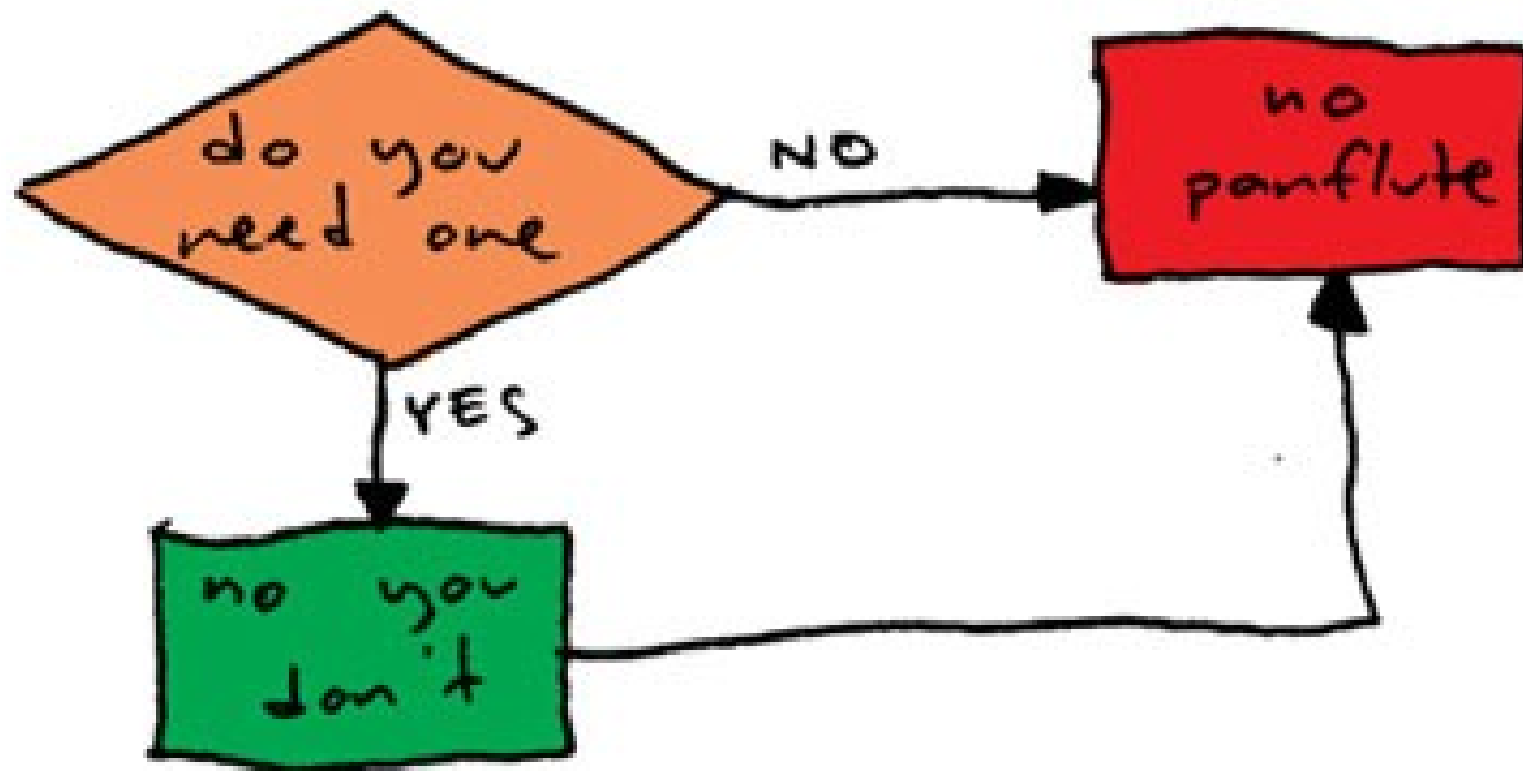
A Social Network



Chemical Bonds



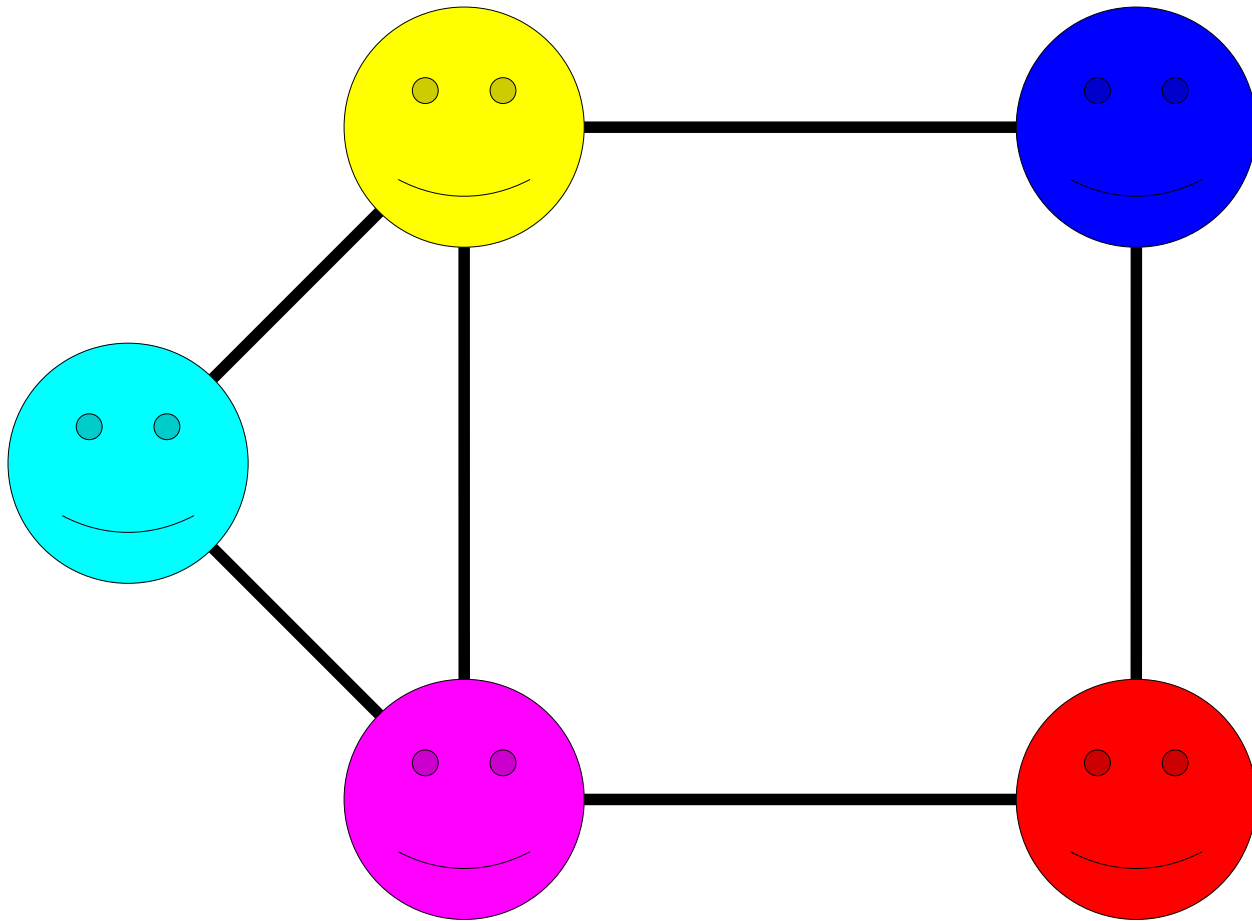
PANFLUTE FLOWCHART



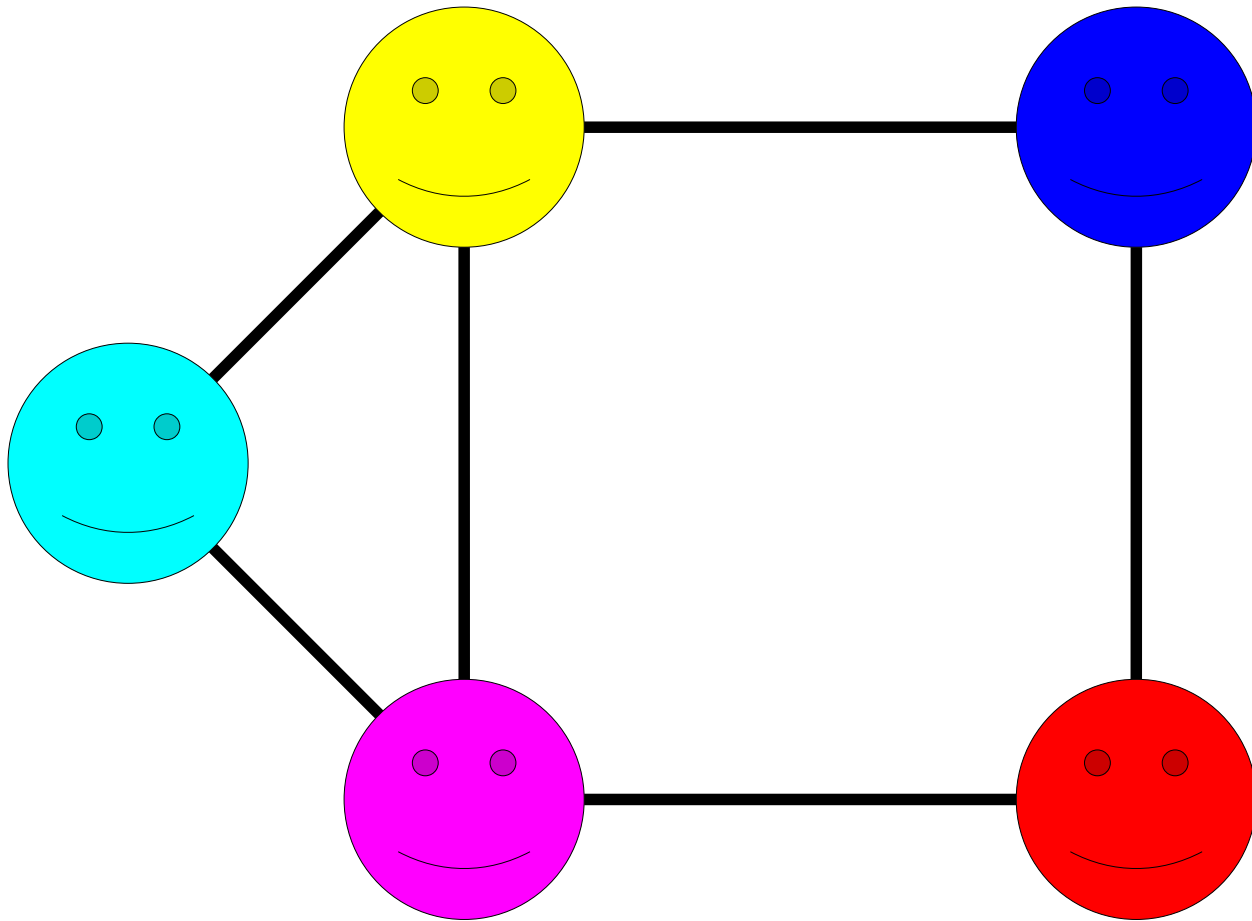
A *graph* is a mathematical structure for representing relationships.

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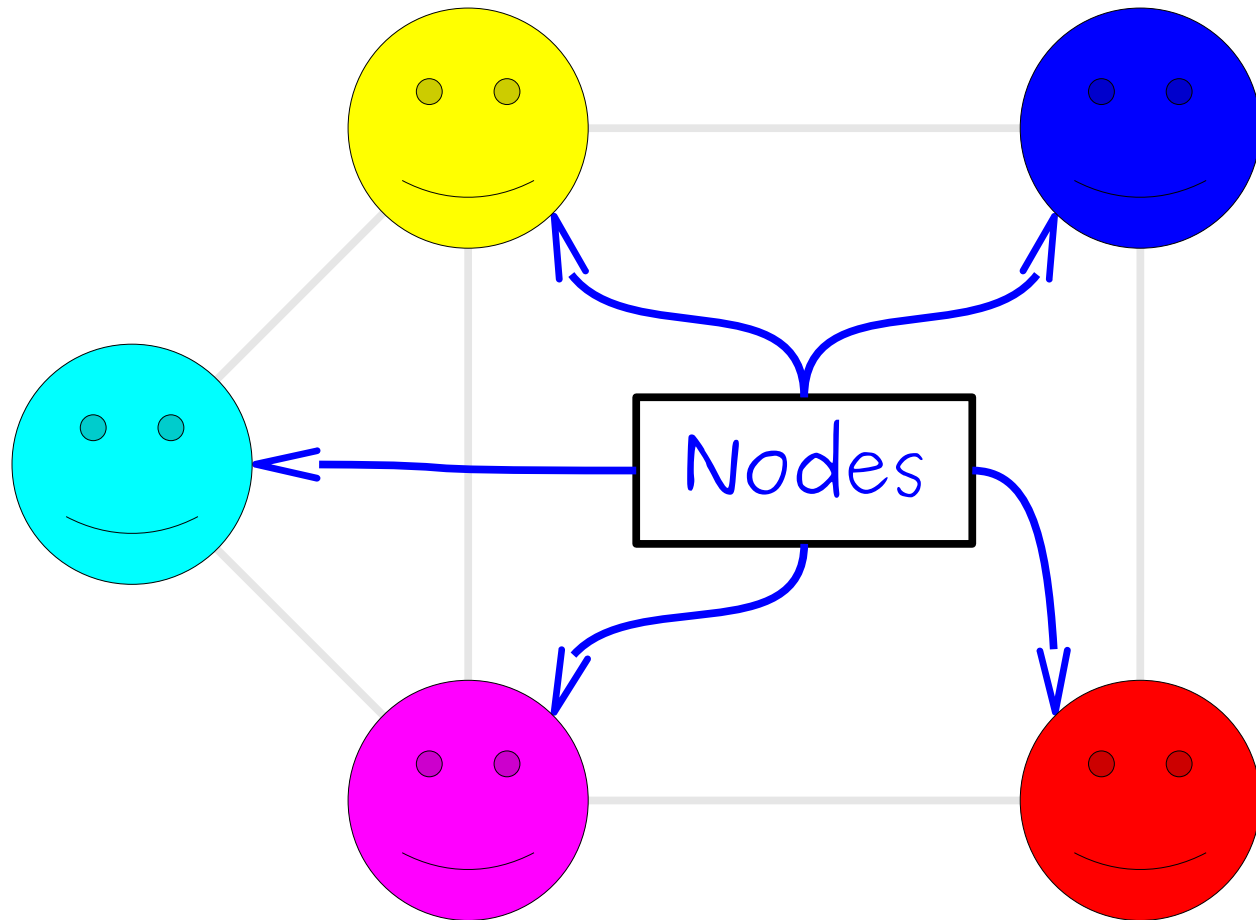


A **graph** is a mathematical structure for representing relationships.



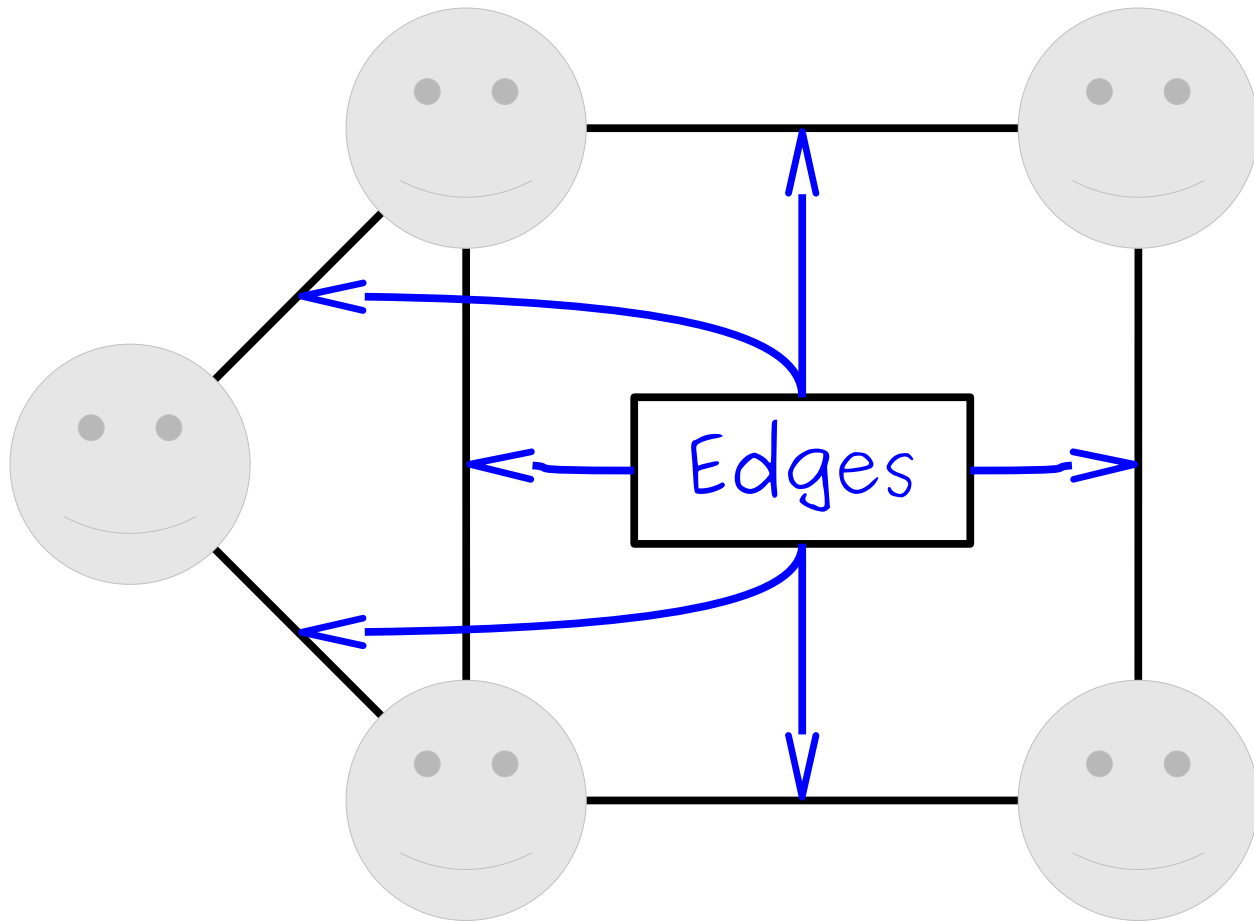
A graph consists of a set of **nodes** connected by **edges**.

A **graph** is a mathematical structure for representing relationships.



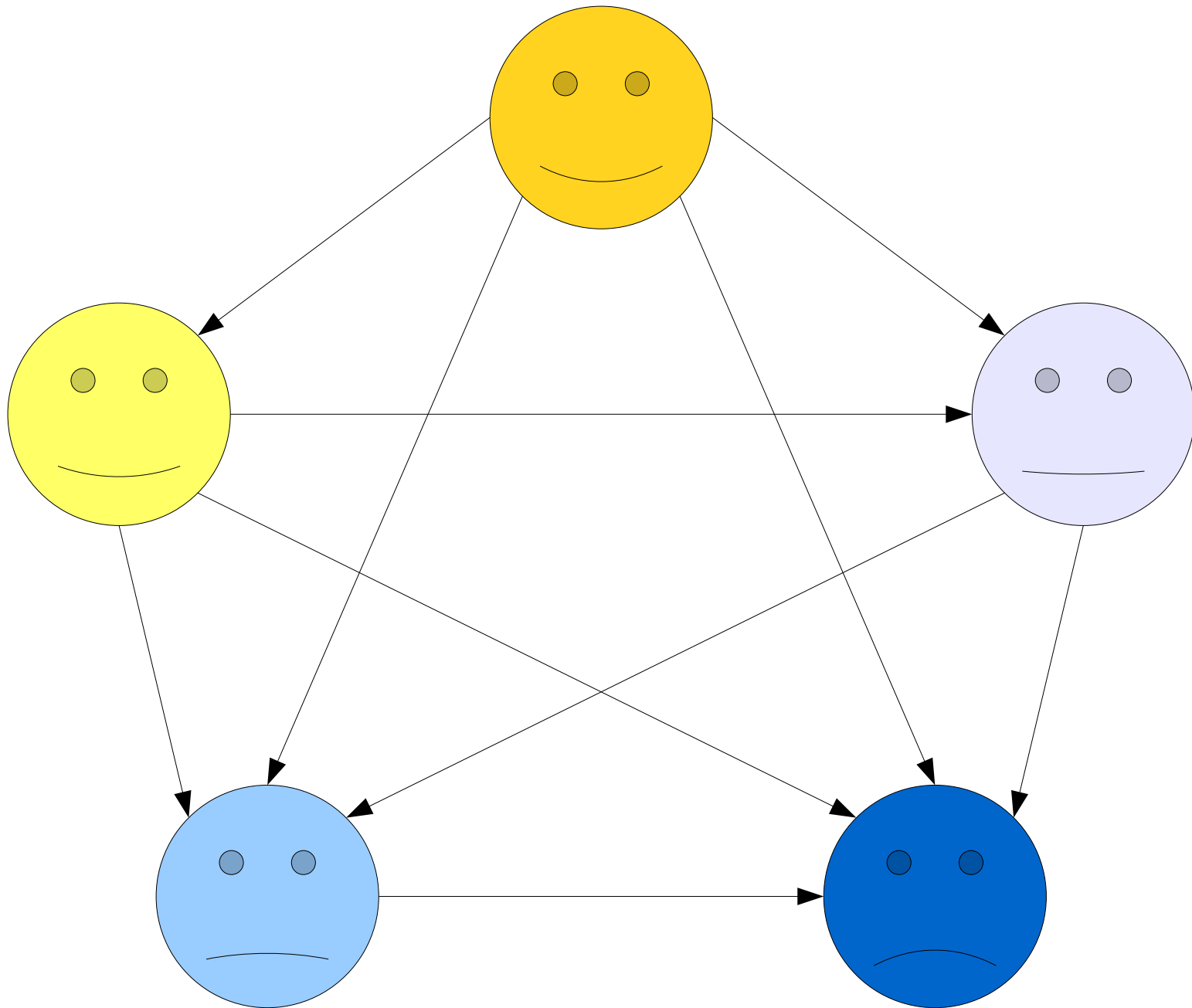
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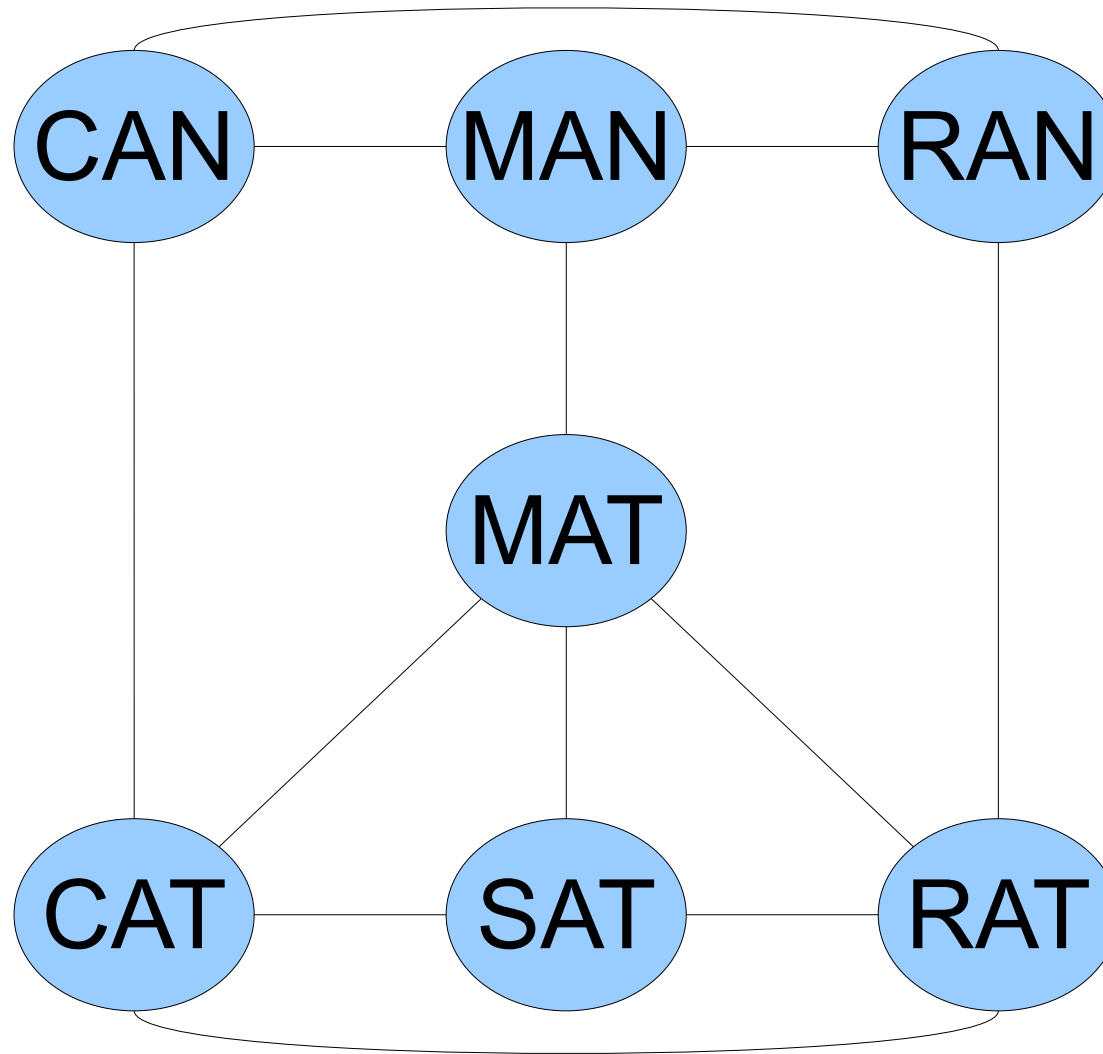


A graph consists of a set of **nodes** connected by **edges**.

Some graphs are *directed*.



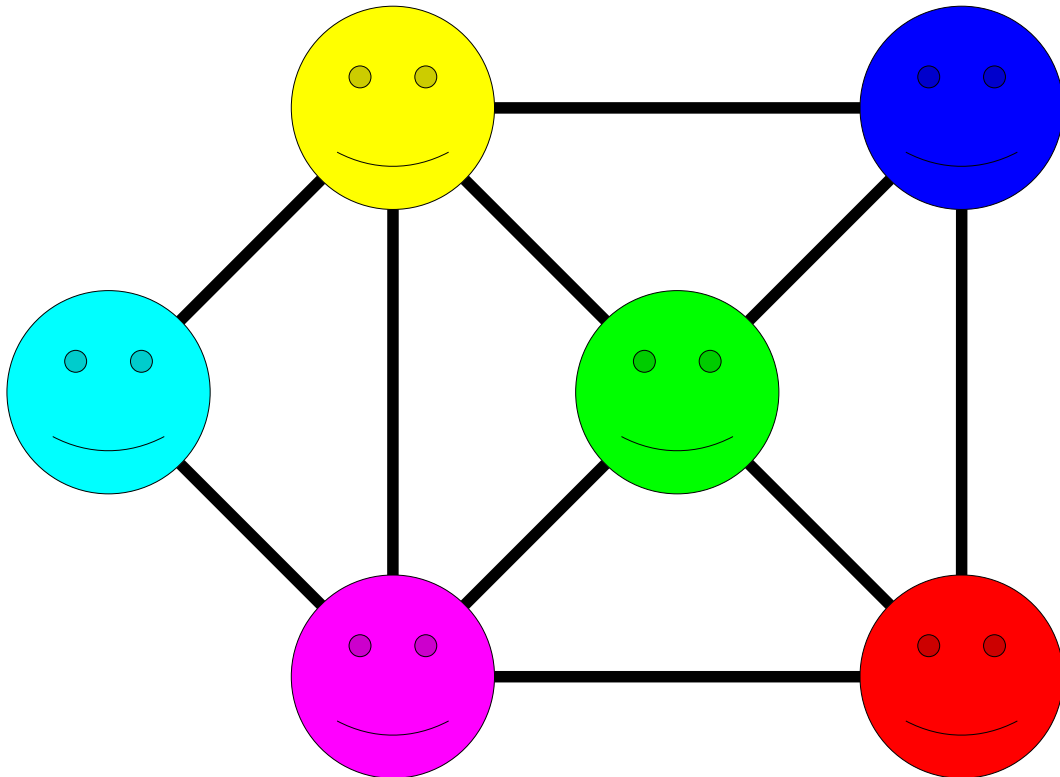
Some graphs are *undirected*.



How can we represent graphs in C++?

Representing Graphs

We can represent a graph as a map from nodes to the list of nodes each node is connected to.



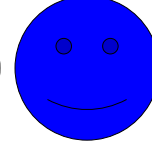
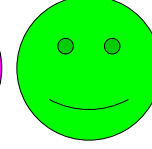
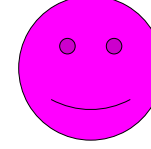
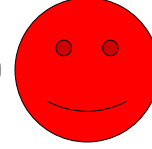
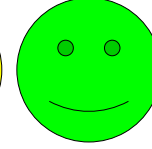
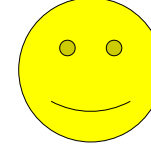
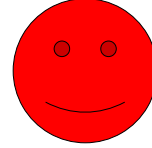
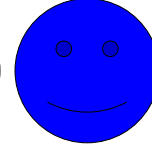
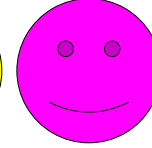
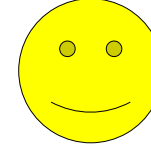
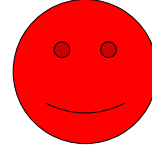
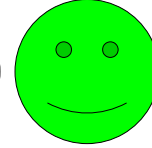
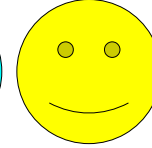
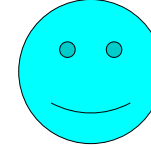
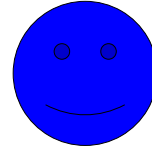
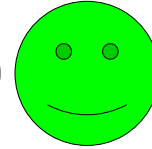
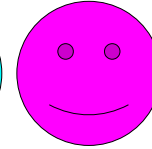
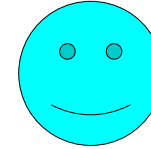
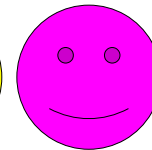
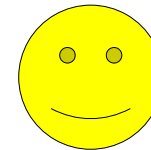
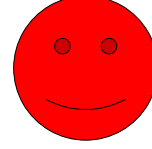
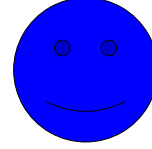
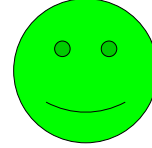
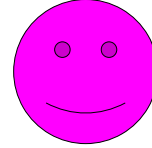
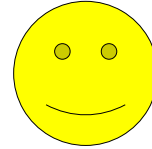
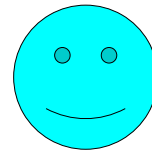
Map<**Node**, Vector<**Node**>>

Node

Vector<**Node**>

Node

Adjacent To



Representing Graphs

- The approach we just saw is called an *adjacency list* and comes in a number of different forms:

Map<string, Vector<string>>

Map<string, Set<string>>

Vector<Vector<int>>

- The core idea is that we have some kind of mapping associating each node with its outgoing edges.

Representing Graphs

The approach we just saw is called an *adjacency list* and comes in a number of different forms:

Map<string, Vector<string>>

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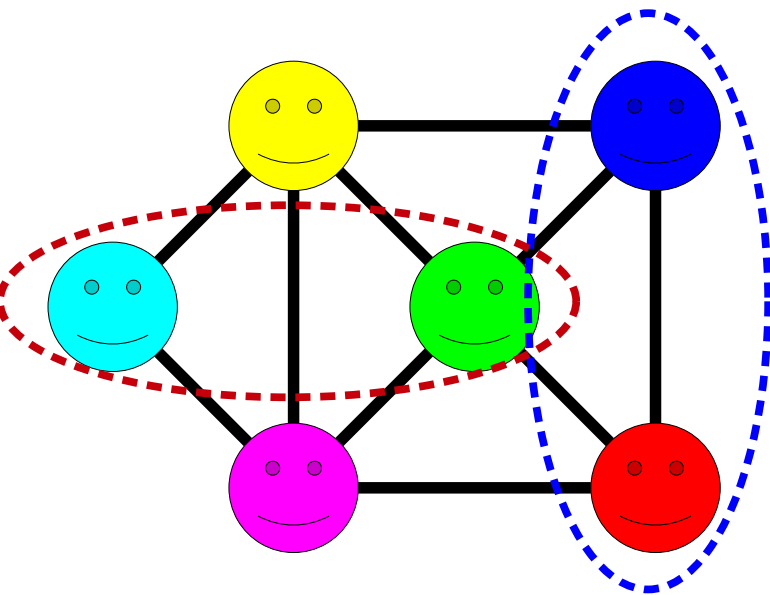
The core idea
of mapping a
its outgoing e

Where have you seen this before?

Answer at



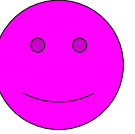
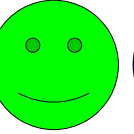
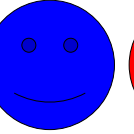
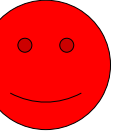


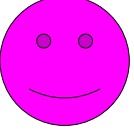
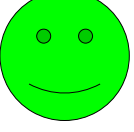
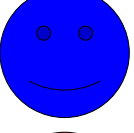
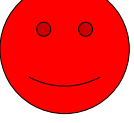
<https://pollev.com/cs106bwin23>

Other Graph Representations

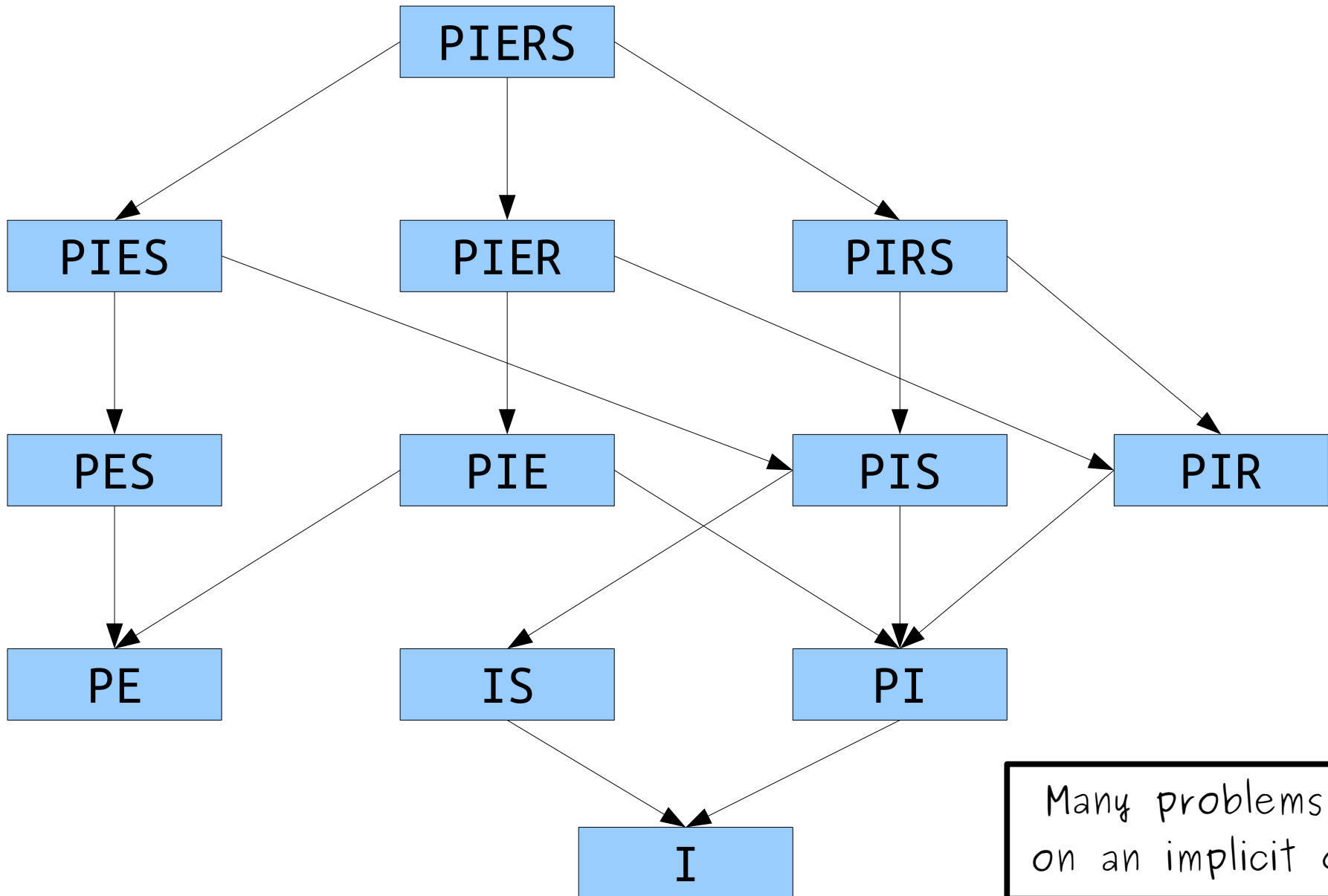


This representation is called an *adjacency matrix*.

For those of you in Math 51: if A is an adjacency matrix for a graph G , what is the significance of the matrix A^2 ?

						
	0	1	1	0	0	0
	1	0	1	1	1	0
	1	1	0	1	0	1
	0	1	1	0	1	1
	0	1	0	1	0	1
	0	0	1	1	1	0



























Other Representations



You'll find graphs just
about everywhere you look.

They're an *extremely* versatile and
powerful abstraction to be aware of.

Going forward, unless stated otherwise,
assume we're using an *adjacency list*.

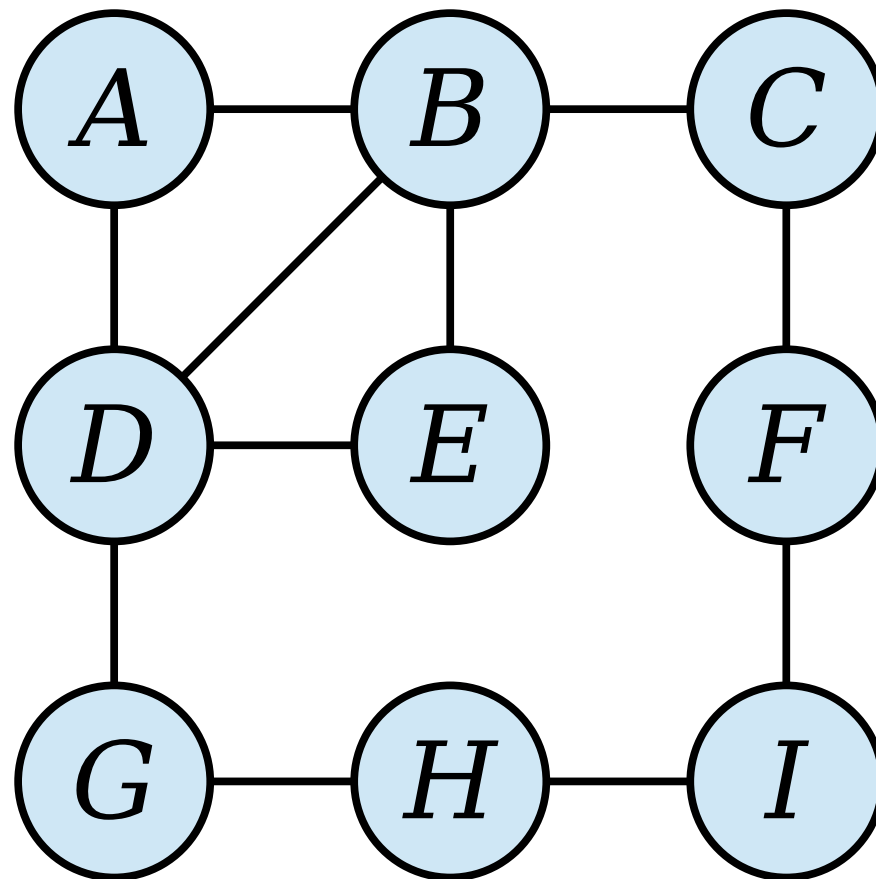
Node	Adjacent To
	 
	   
	   
	   
	  
	  

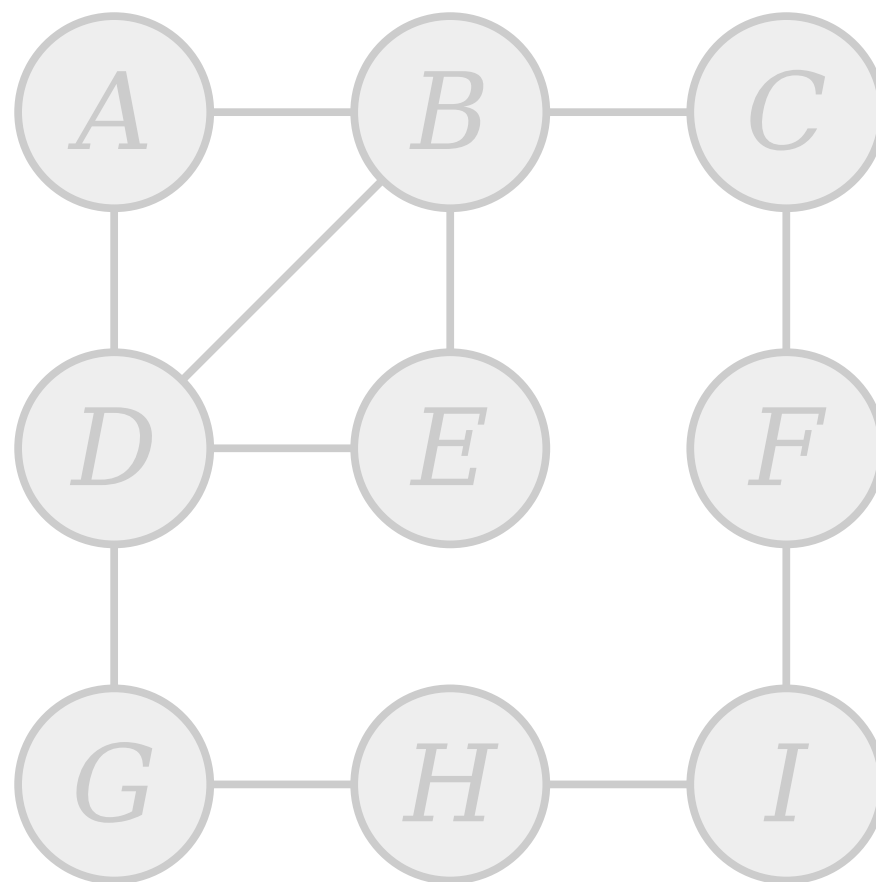
Traversing Graphs

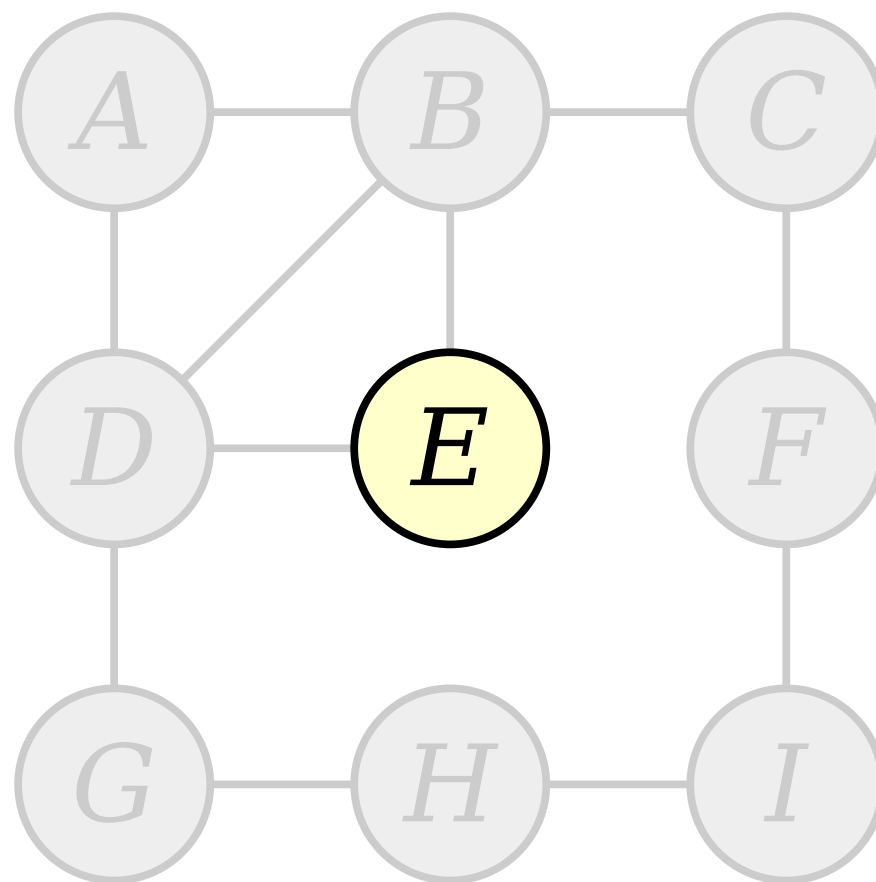
Iterating over a Graph

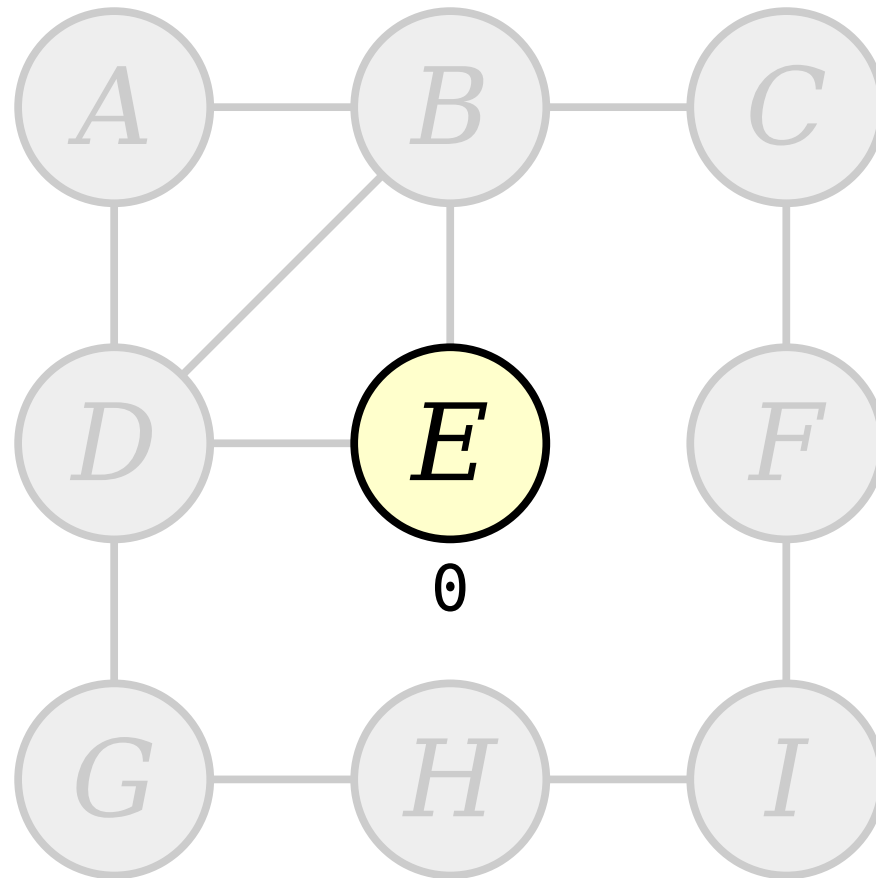
- In a singly-linked list, there's pretty much one way to iterate over the list: start at the front and go forward!
- In a binary search tree, there are many traversal strategies:
 - An ***inorder traversal*** that produces all the elements in sorted order.
 - A ***postorder traversal*** used to delete all the nodes in the BST.
- There are *many* ways to iterate over a graph, each of which have different properties.

One Search Strategy

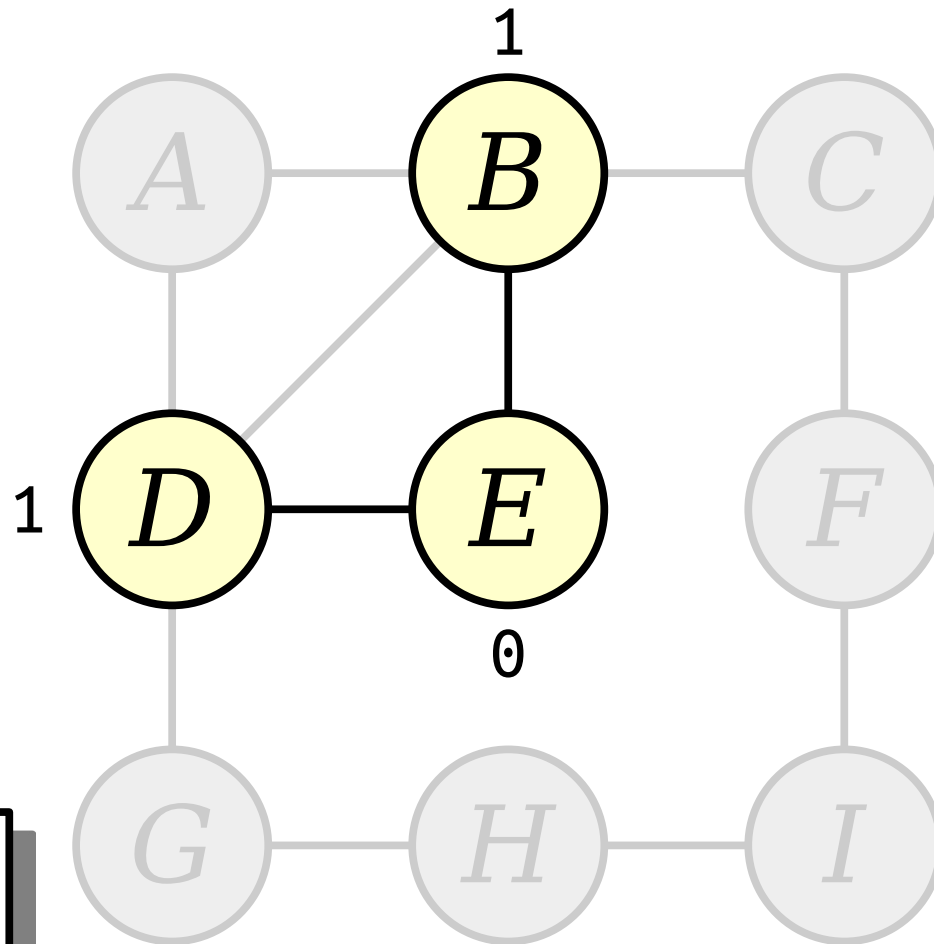




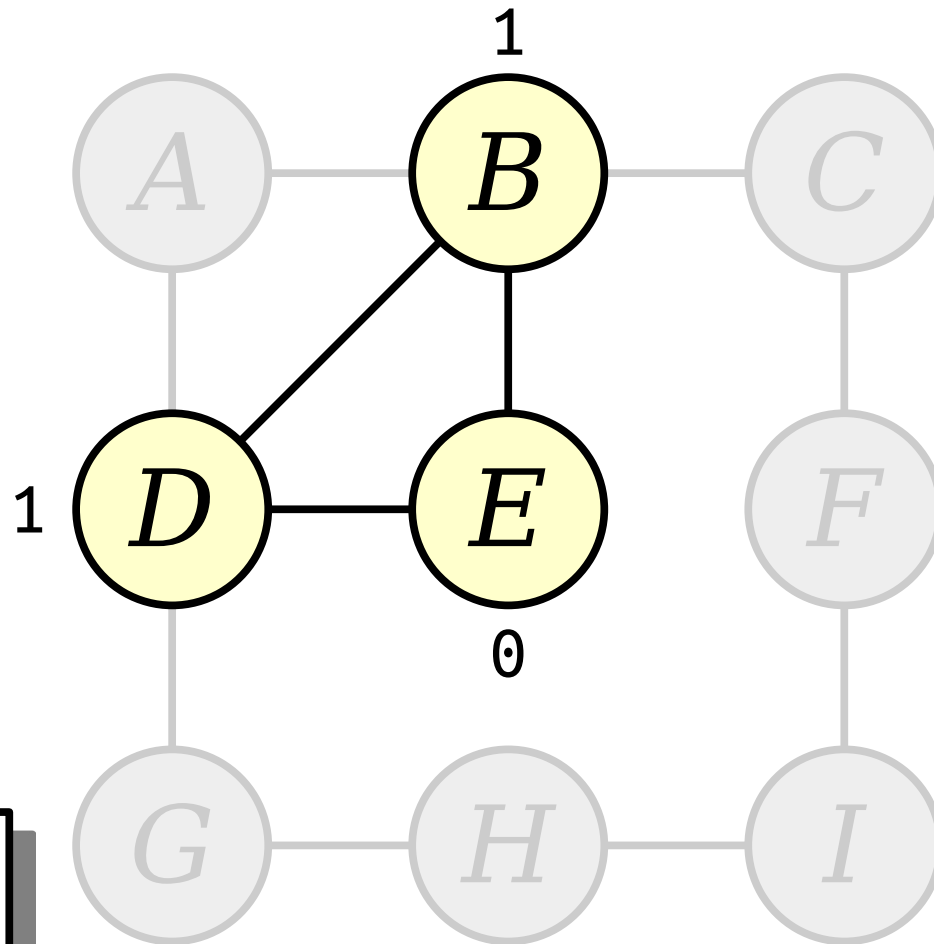




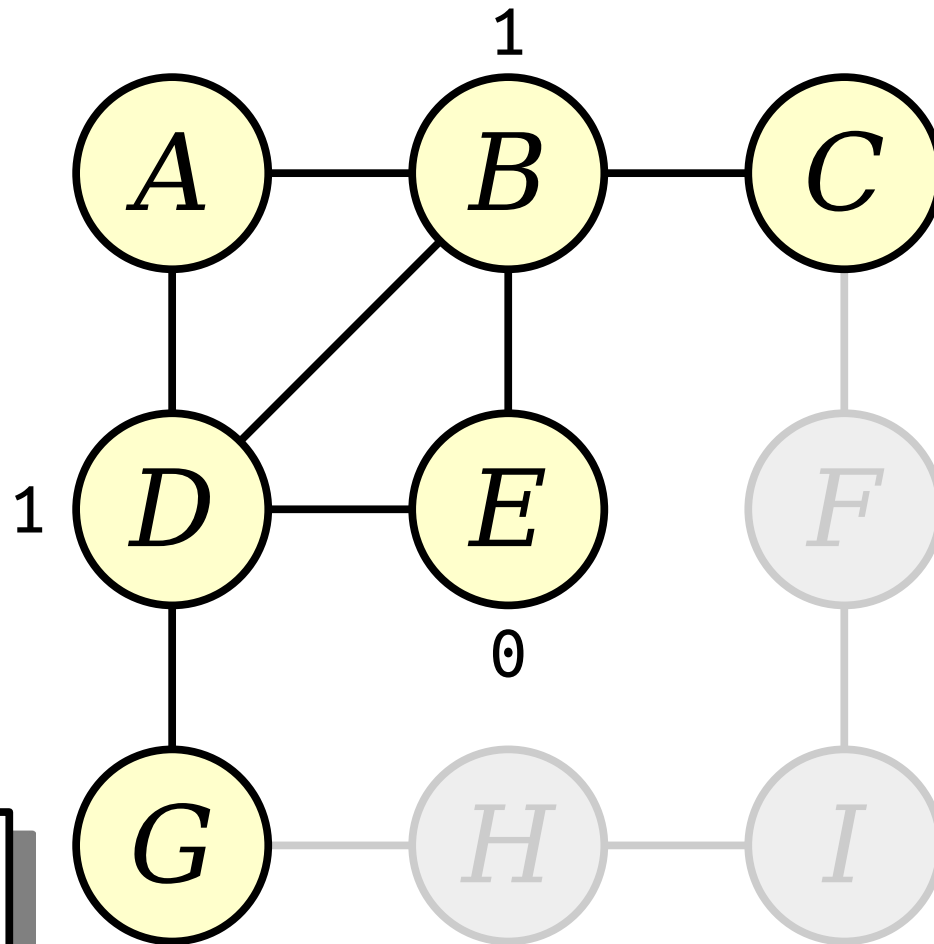
Core idea: Find everything one hop away from the start, then two hops away, then three hops away, etc.



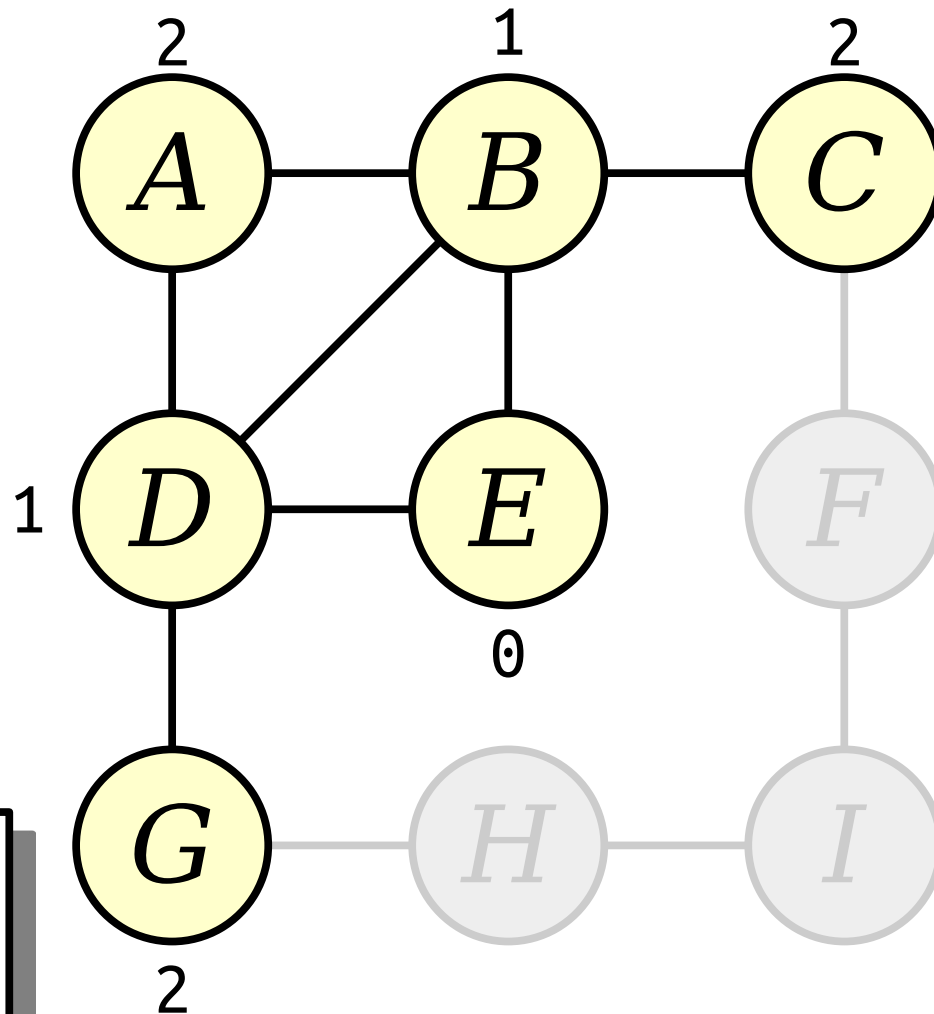
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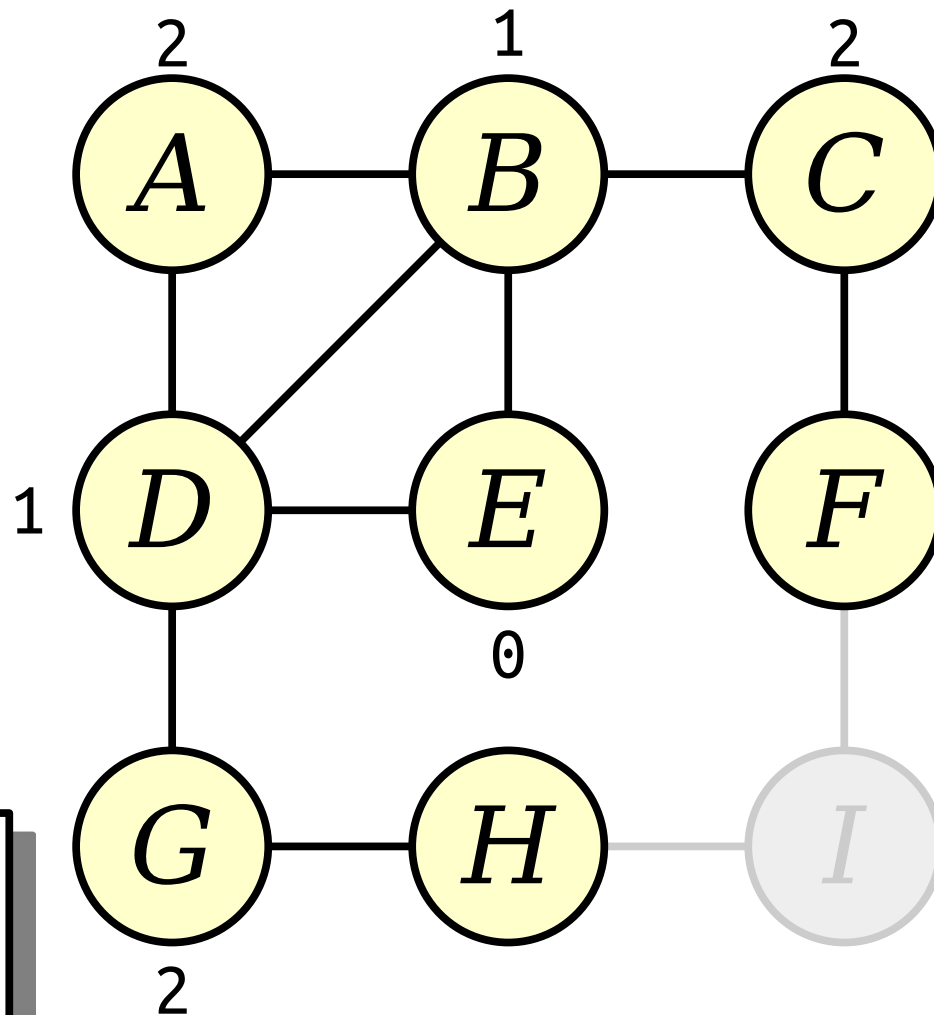
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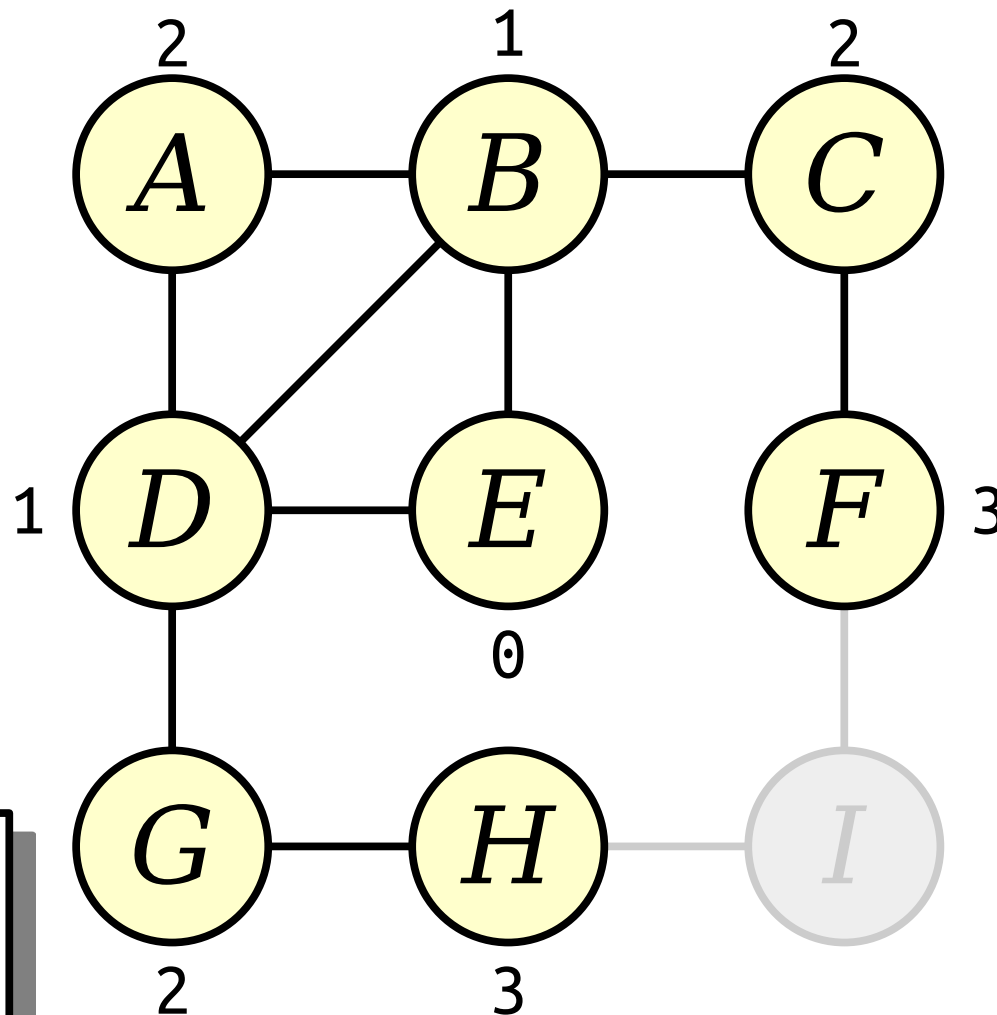
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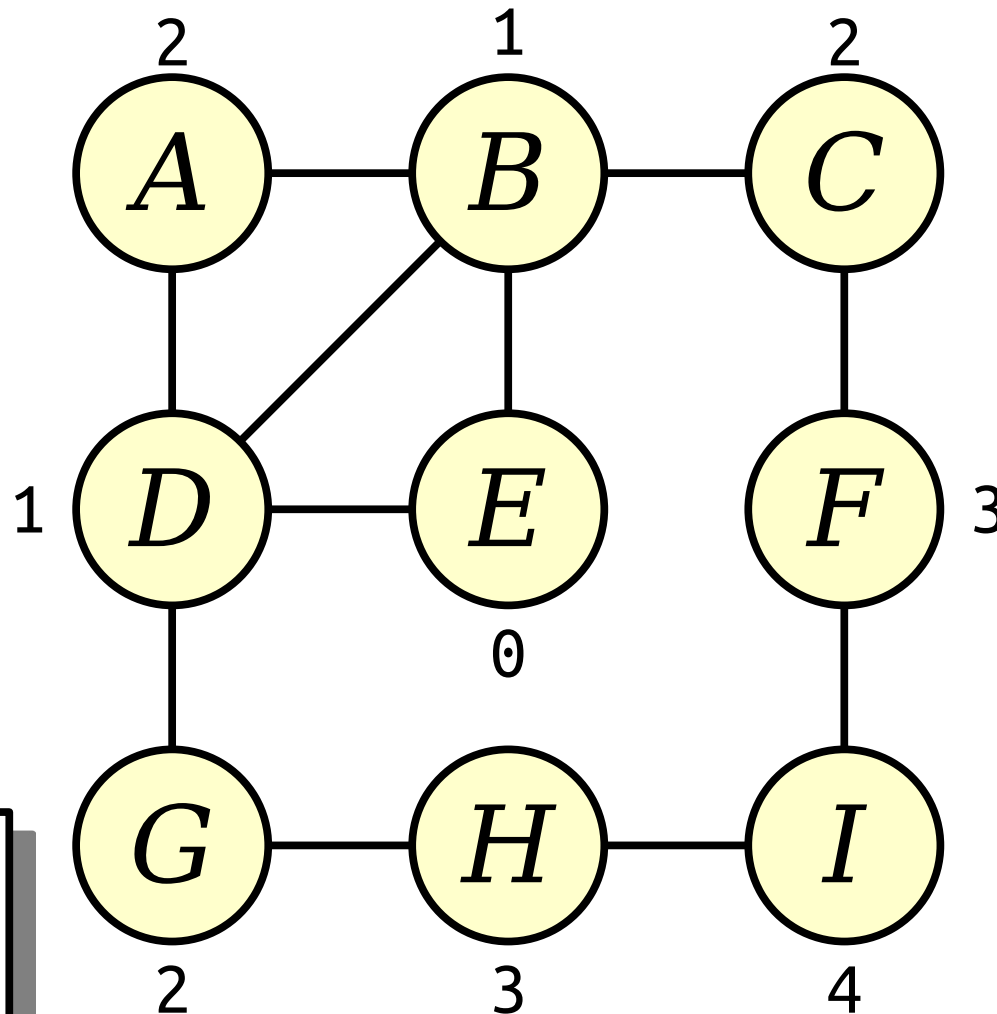
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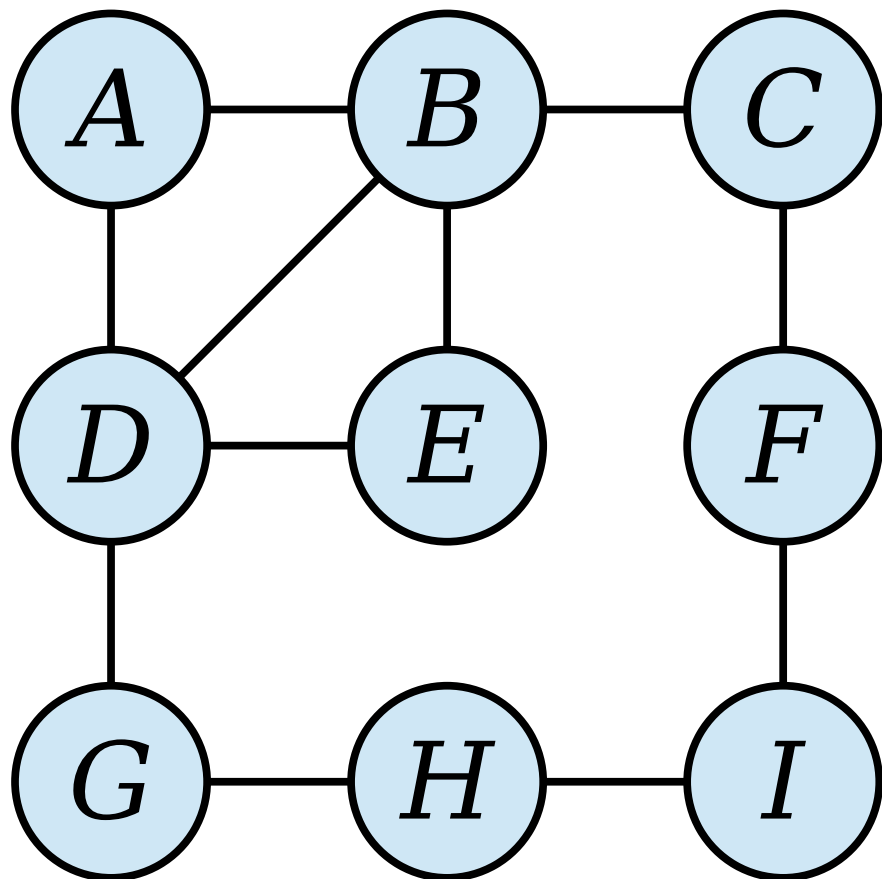


Core idea: Find everything one hop away from the start, then two hops away, then three hops away, etc.

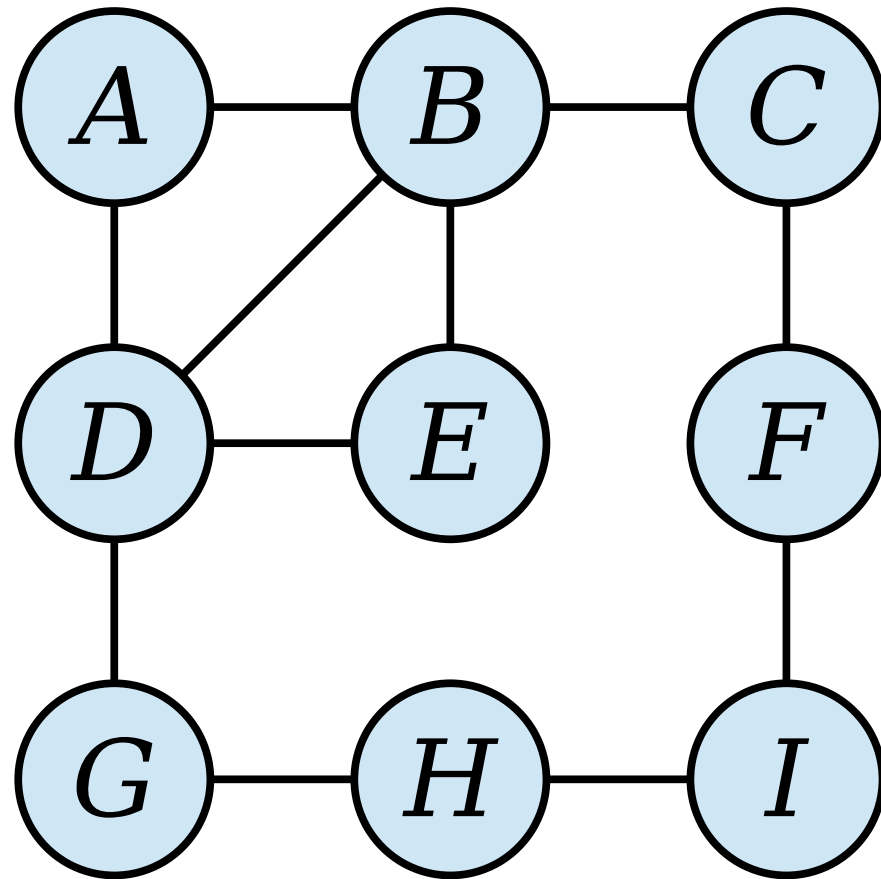


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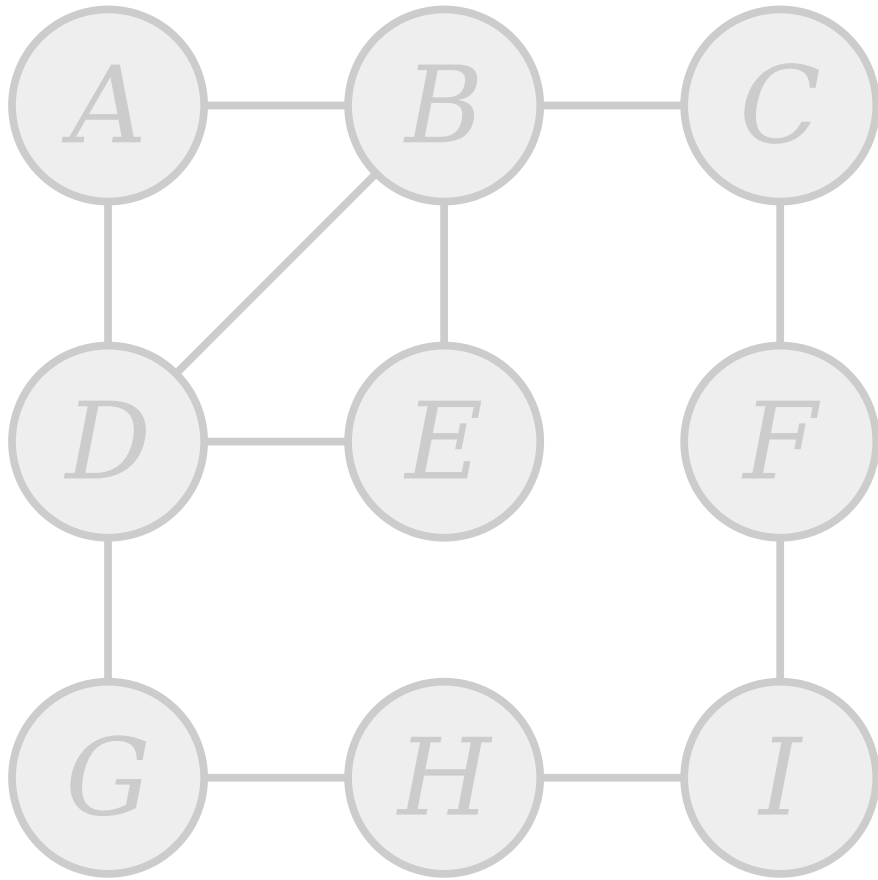
Implementing this Idea



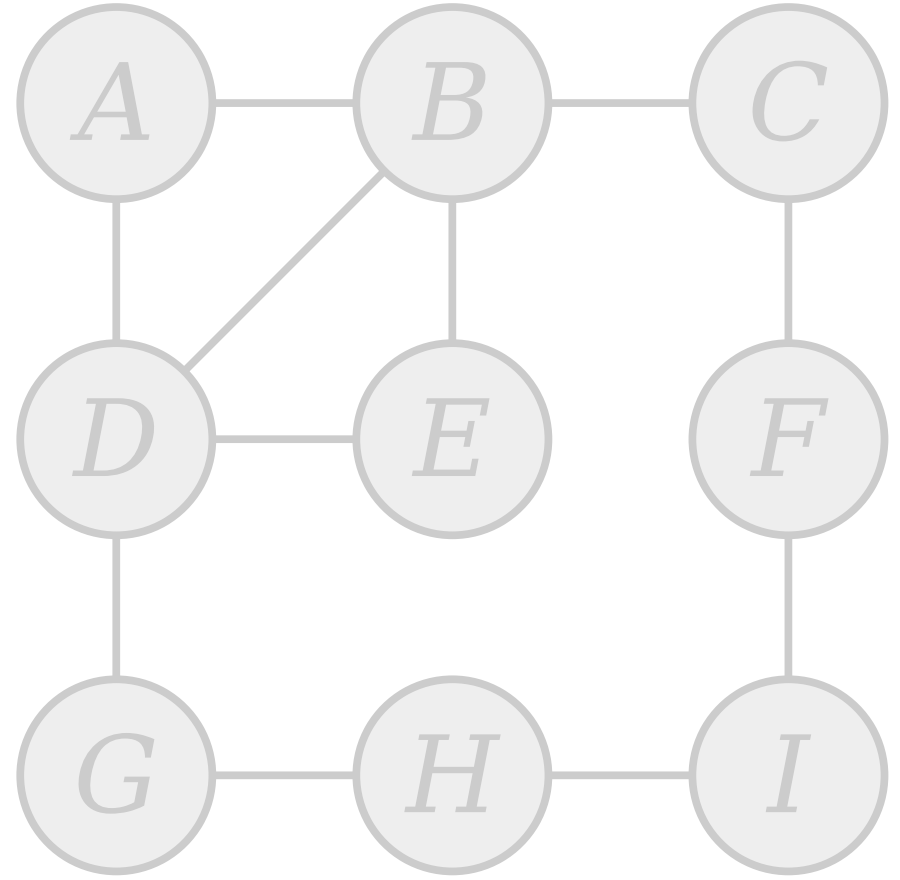
Visit nodes in ascending order of distance from the start node *E*.



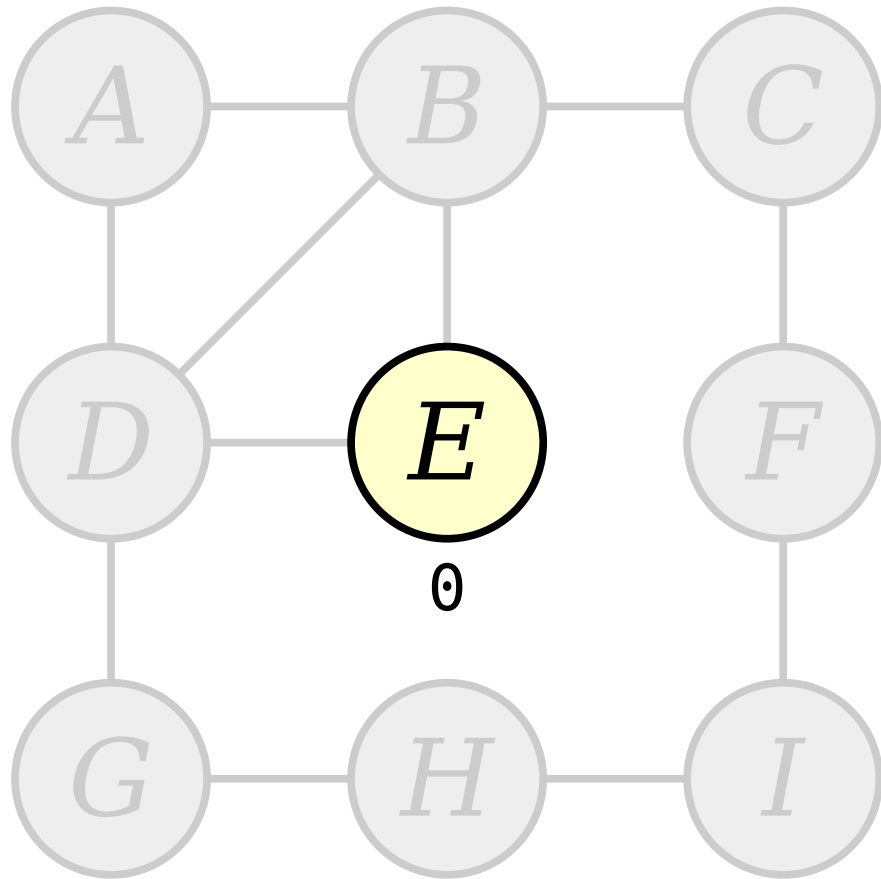
Load newly-discovered nodes into a queue.



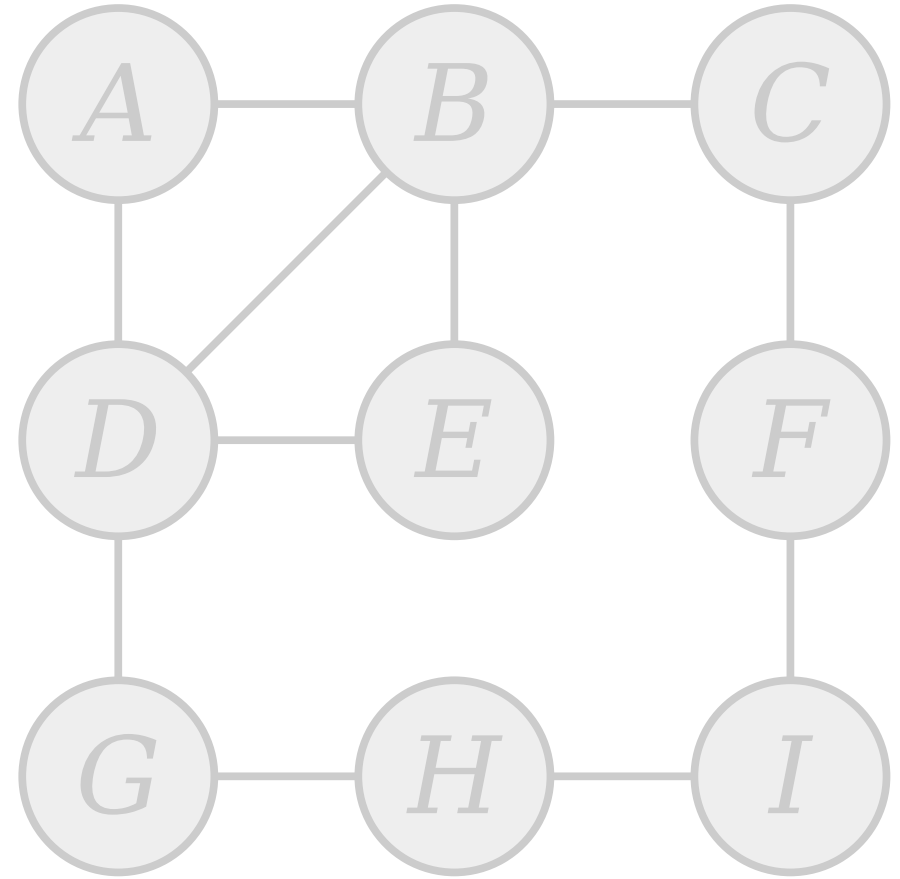
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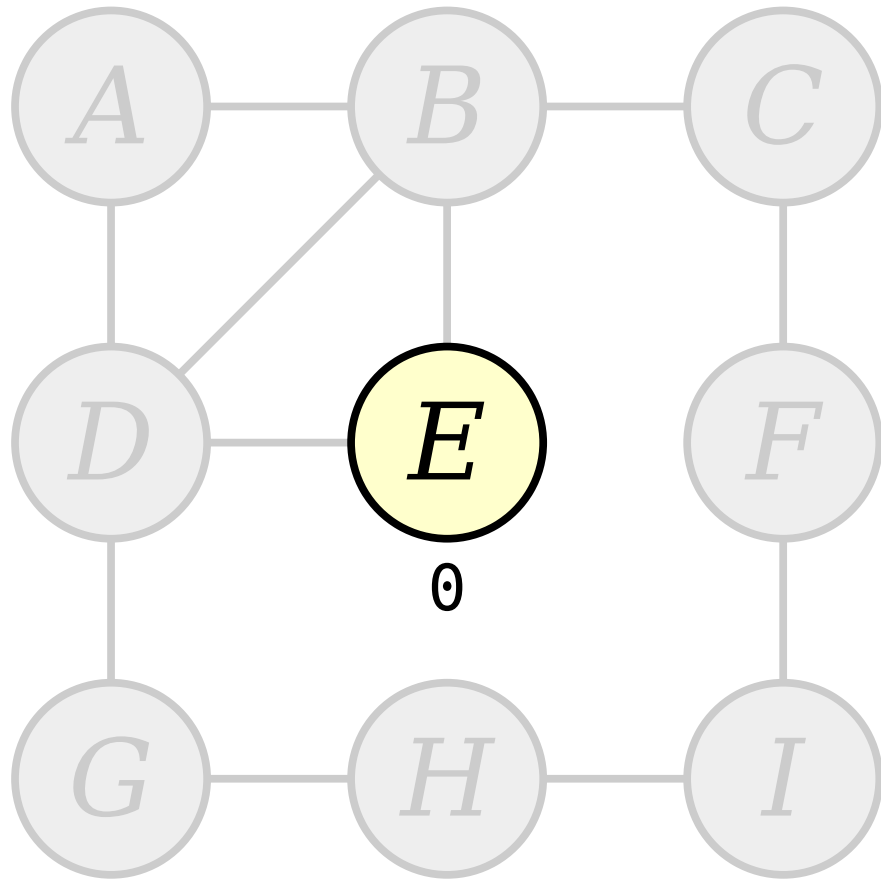
Load newly-discovered nodes into a queue.



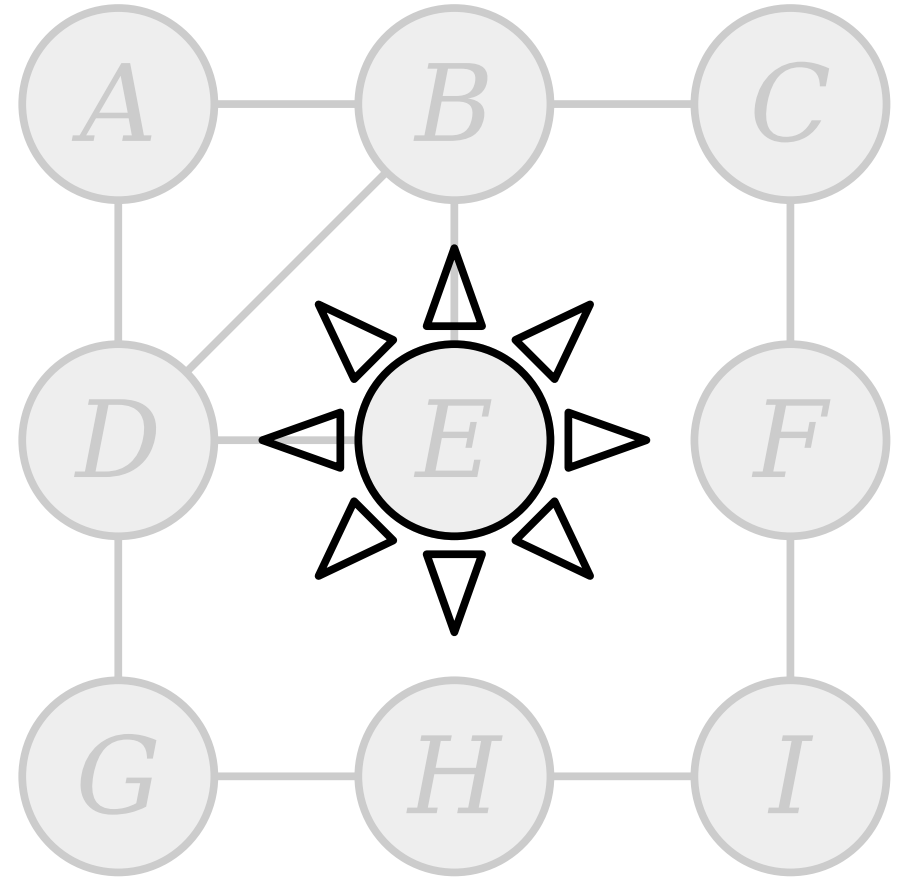
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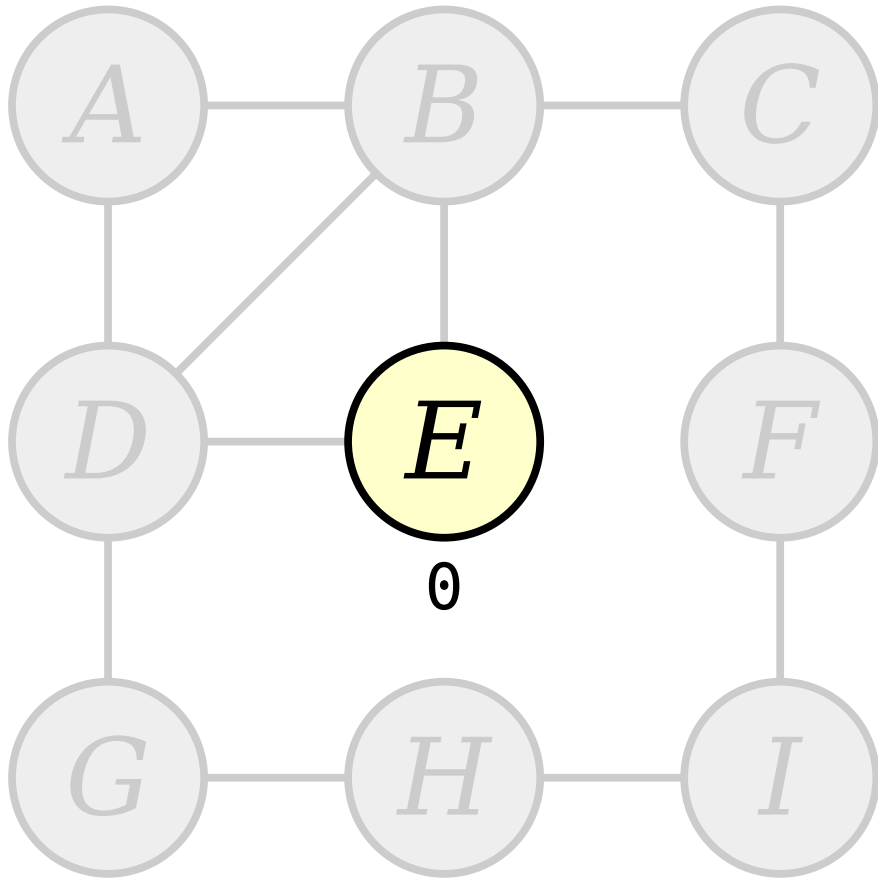


Visit nodes in ascending order of distance from the start node *E*.

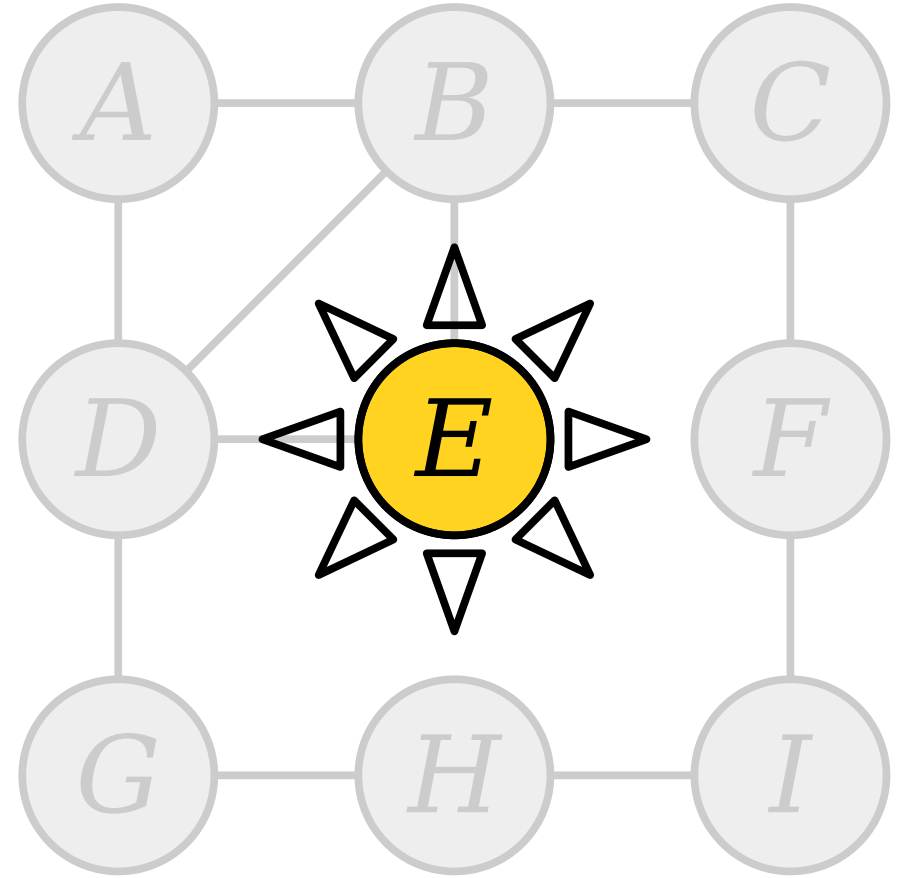


Queue: *E*

Load newly-discovered nodes into a queue.

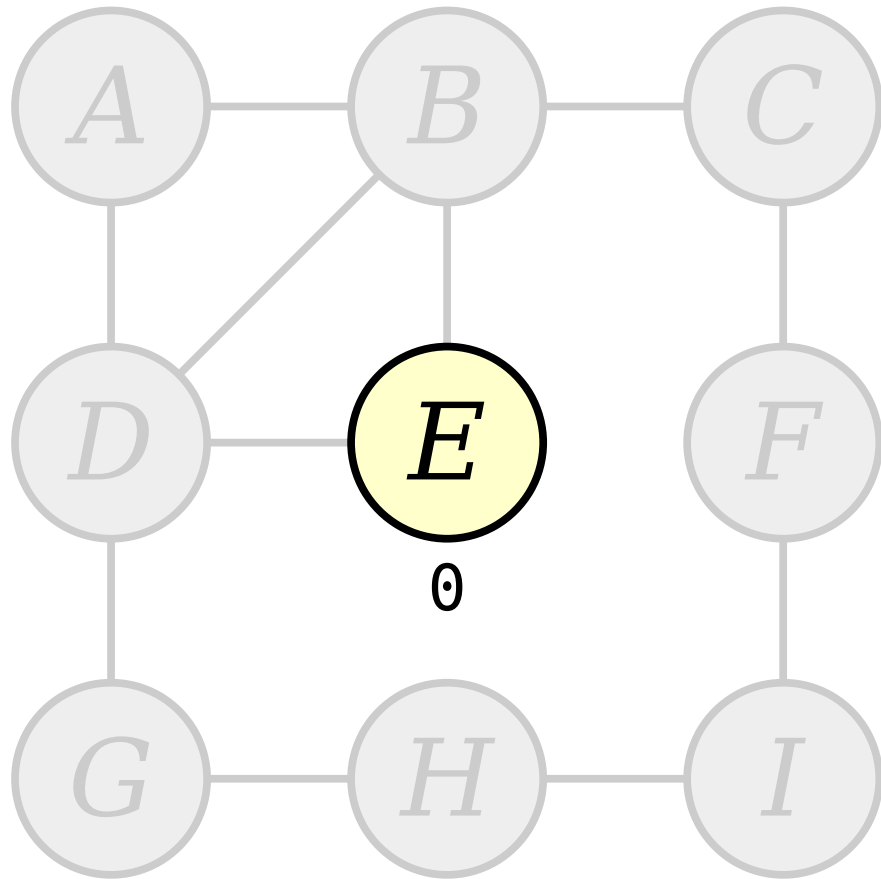


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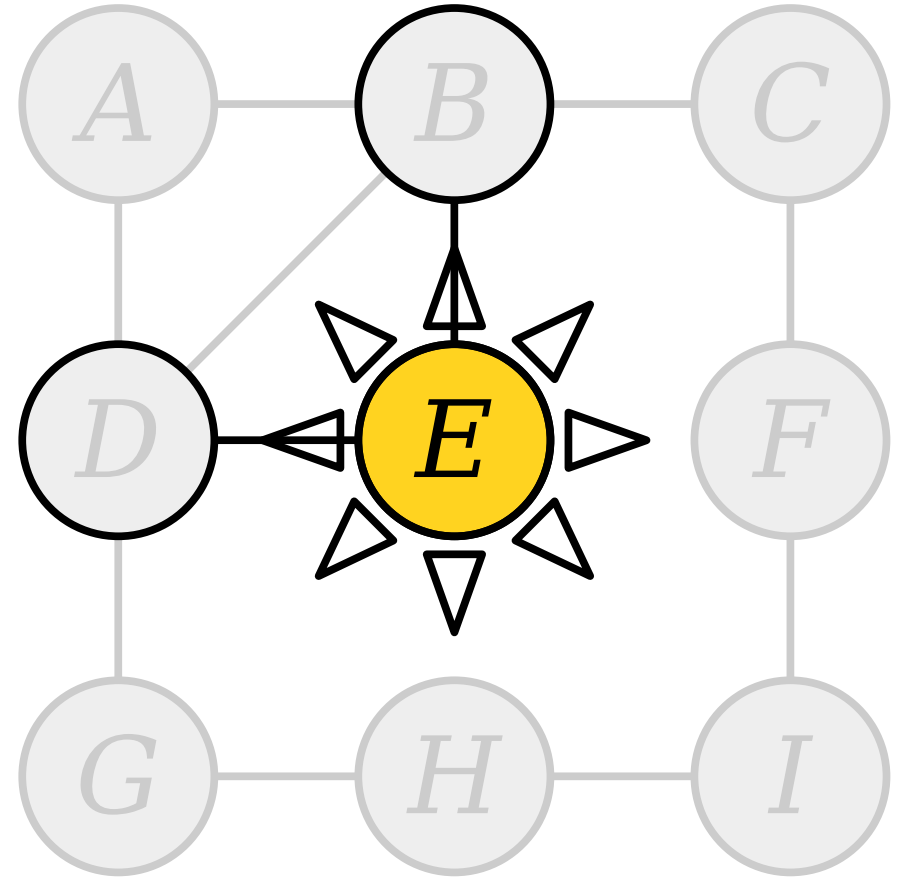


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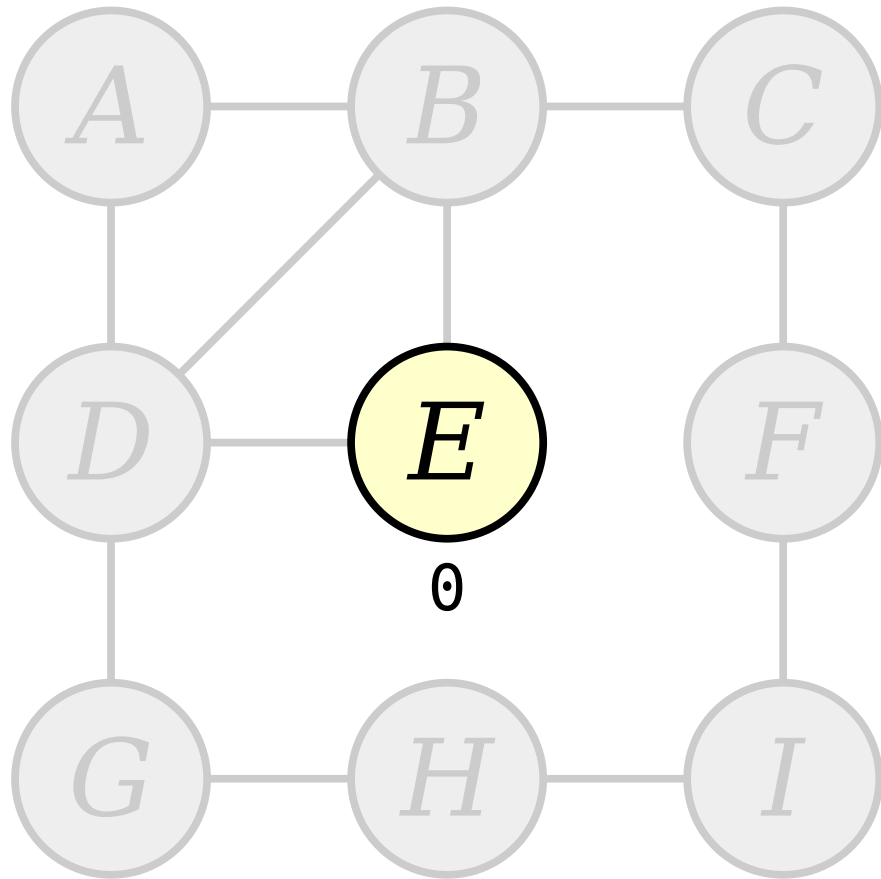


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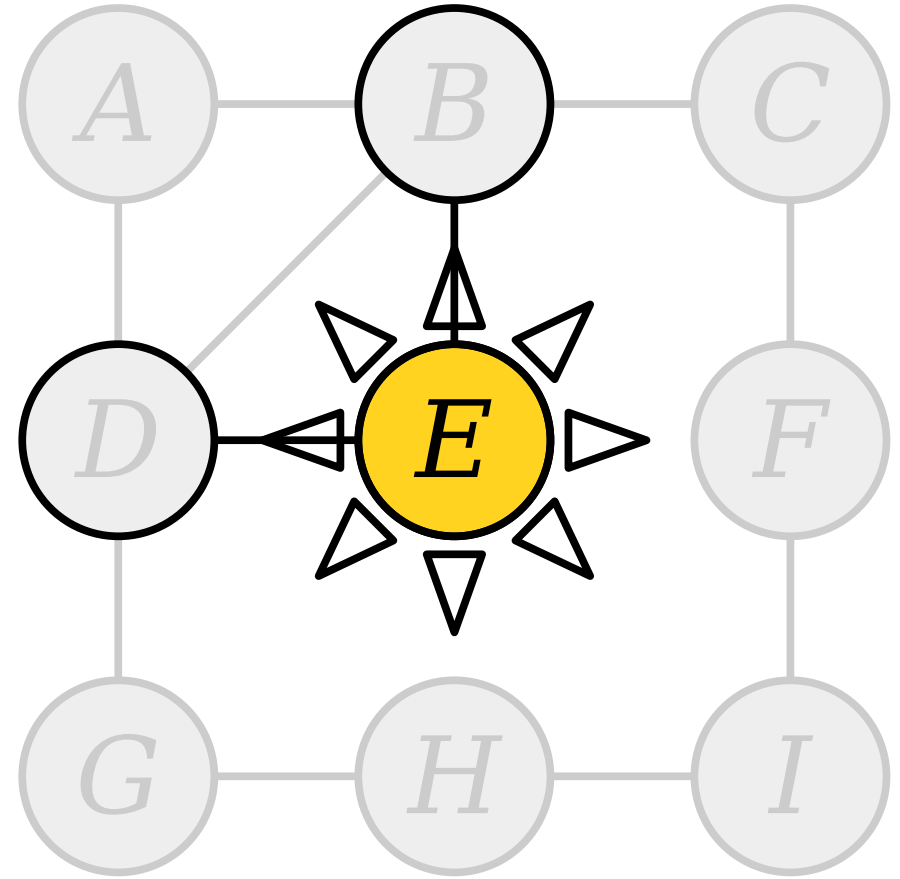


Queue:

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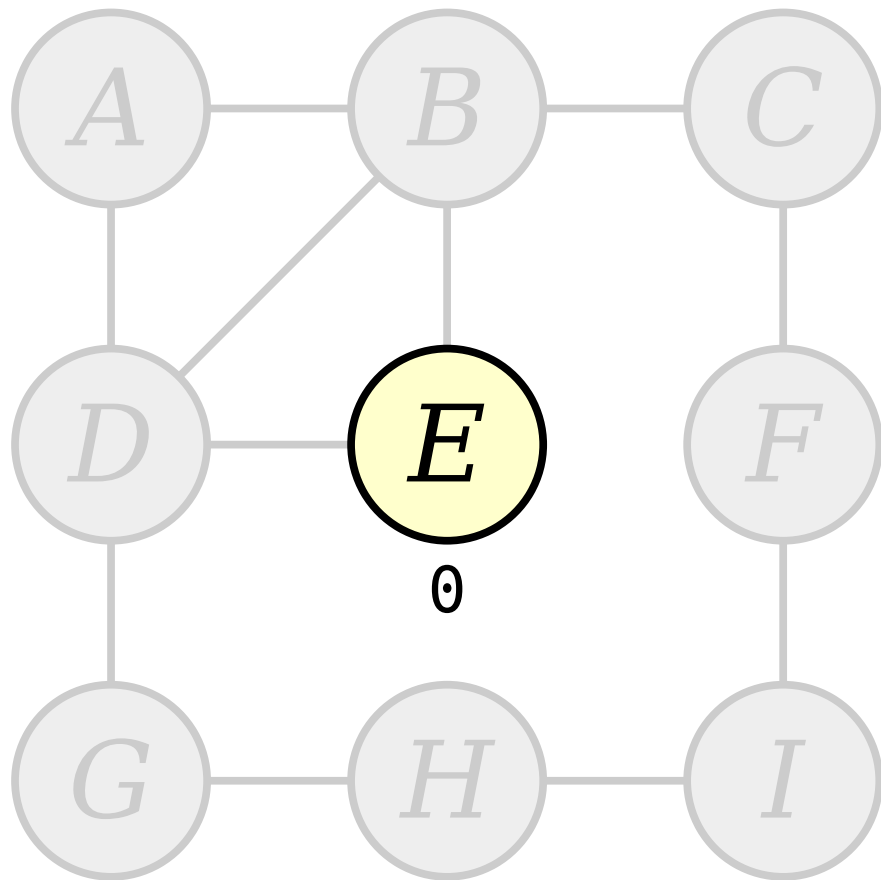


Visit nodes in ascending order of distance from the start node *E*.

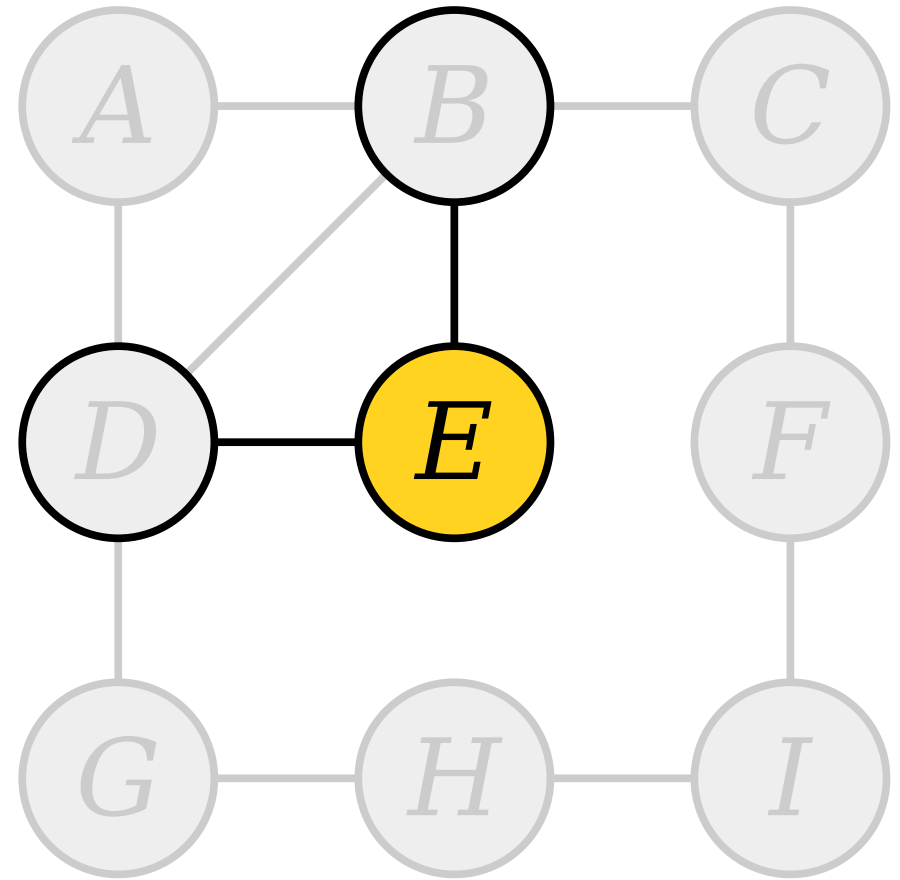


Queue: *D* *B*

Load newly-discovered nodes into a queue.

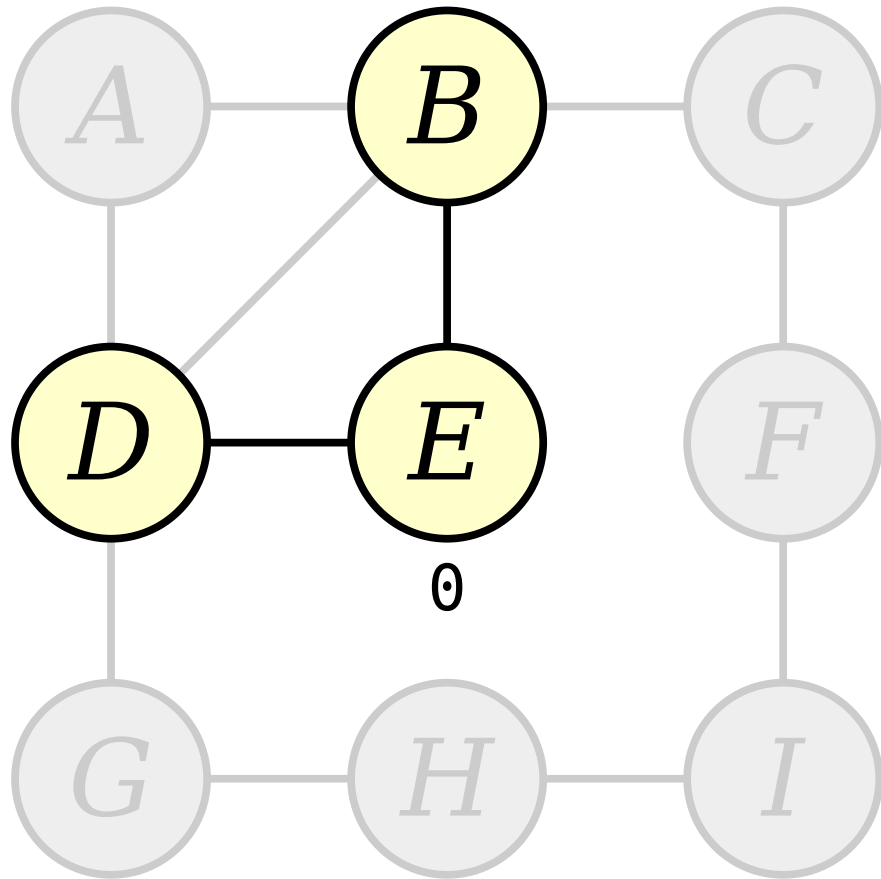


Visit nodes in ascending order of distance from the start node *E*.

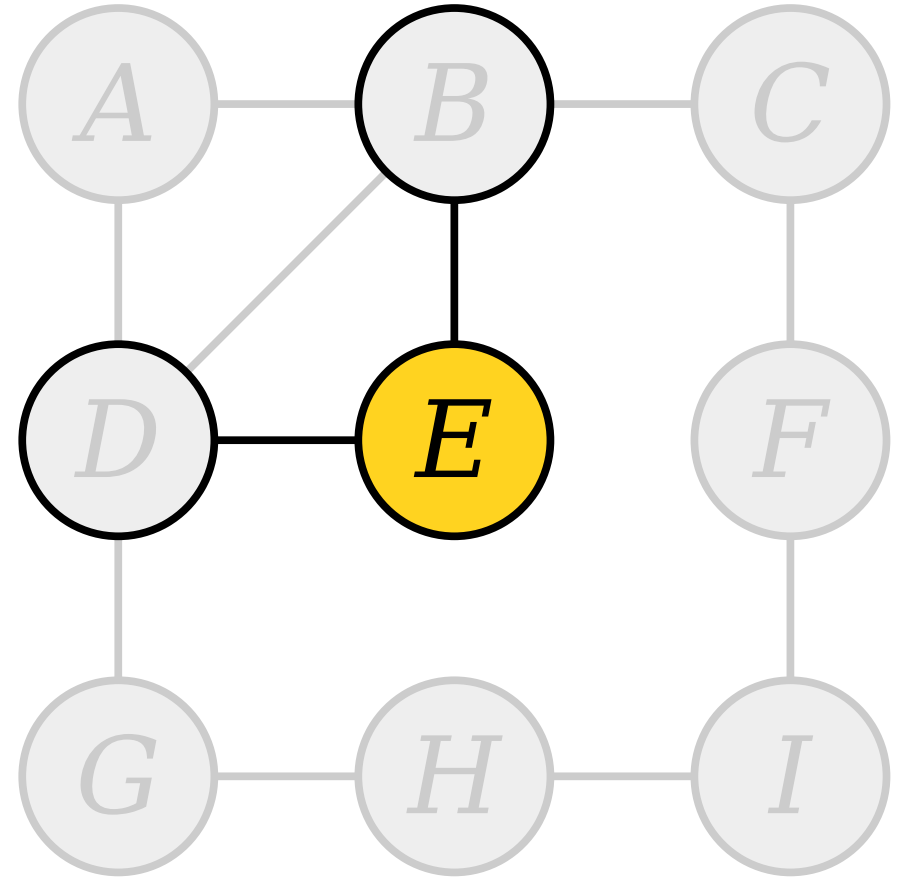


Queue: *D* *B*

Load newly-discovered nodes into a queue.

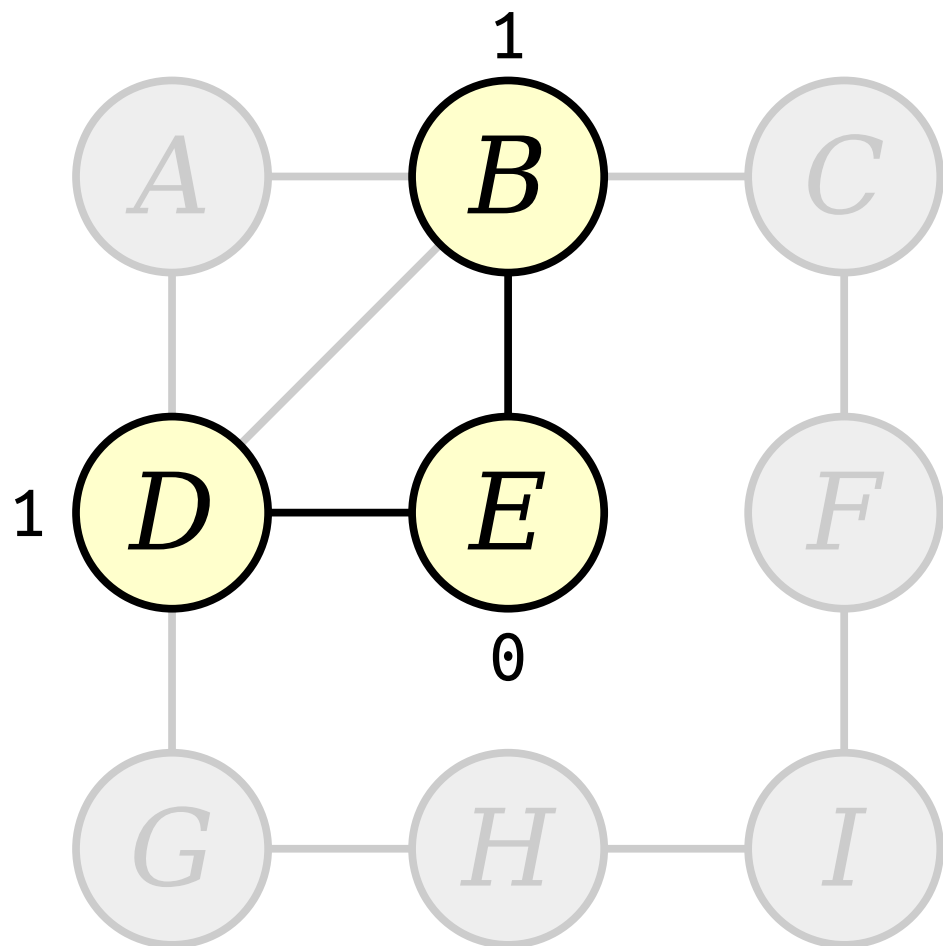


Visit nodes in ascending order of distance from the start node *E*.

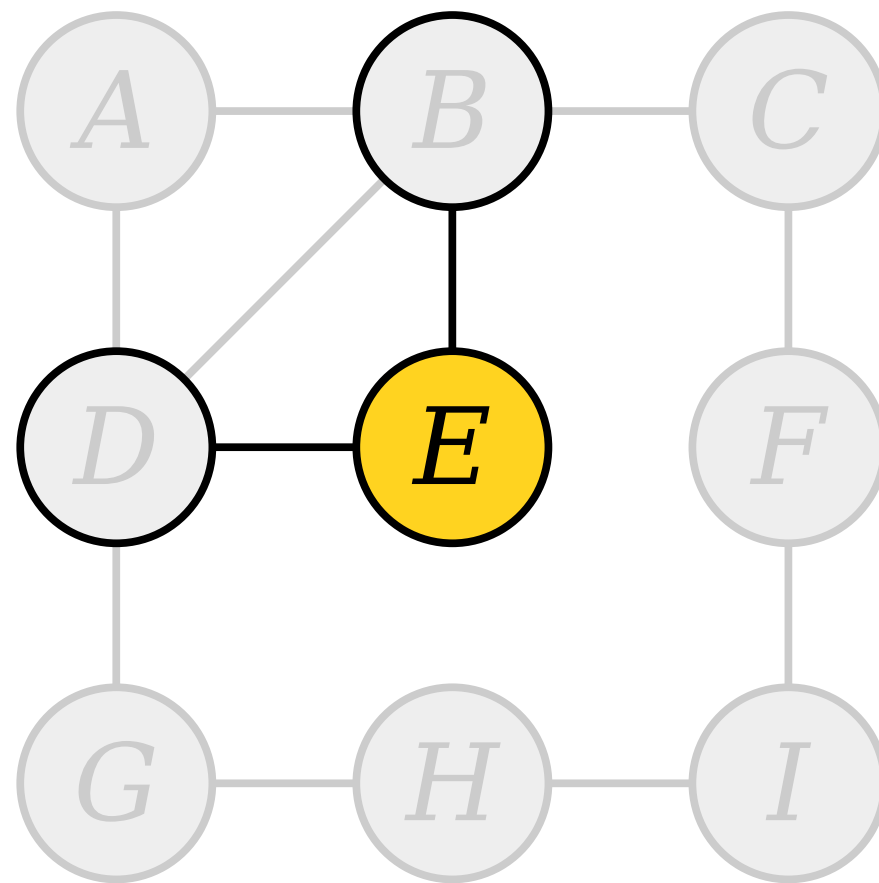


Queue: *D* *B*

Load newly-discovered nodes into a queue.

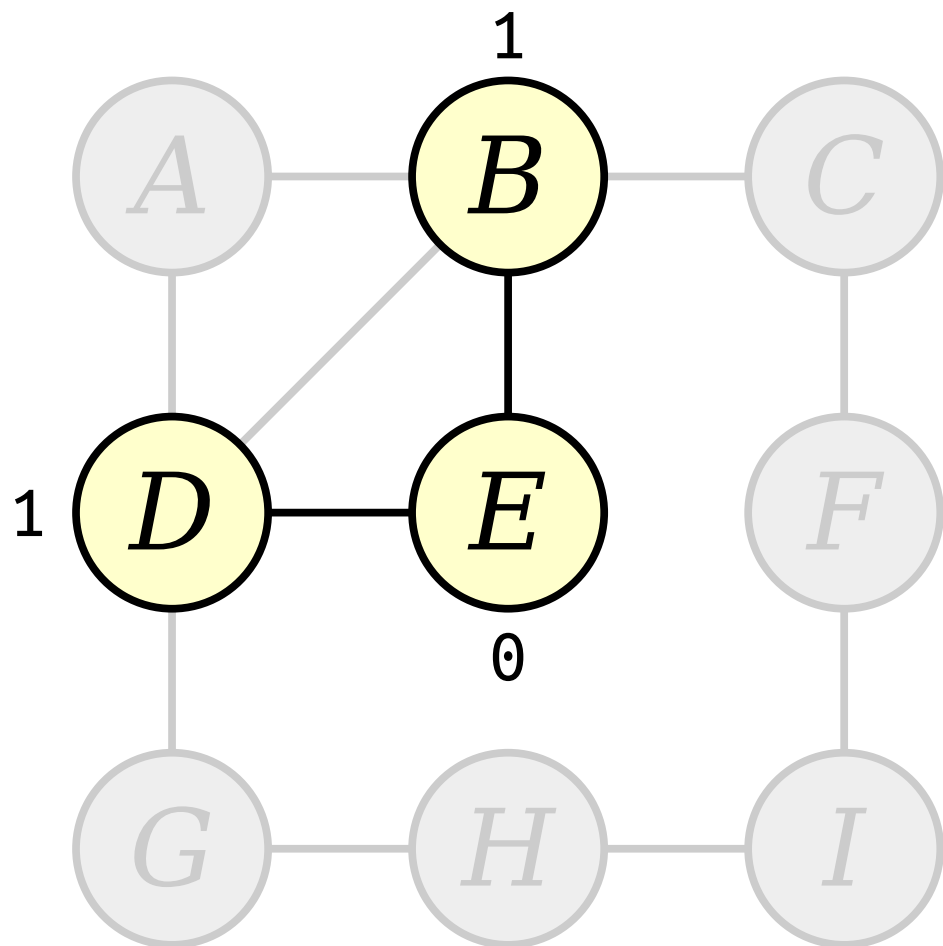


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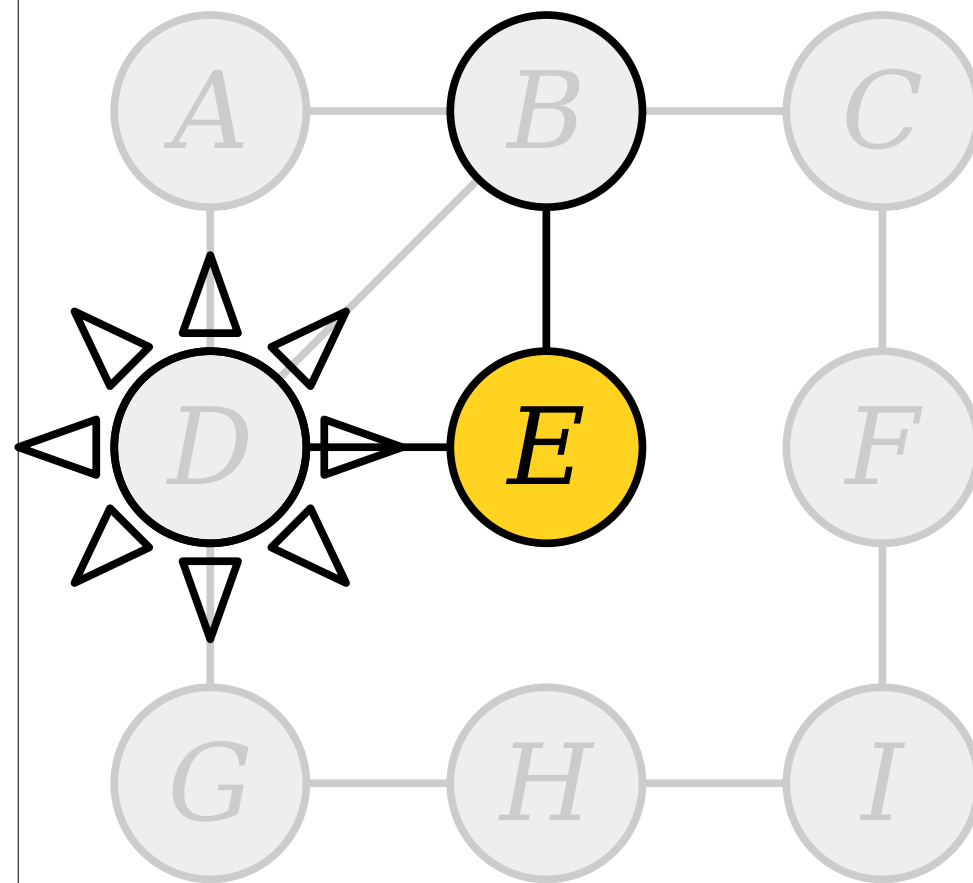


Queue: *D* *B*

Load newly-discovered nodes into a queue.

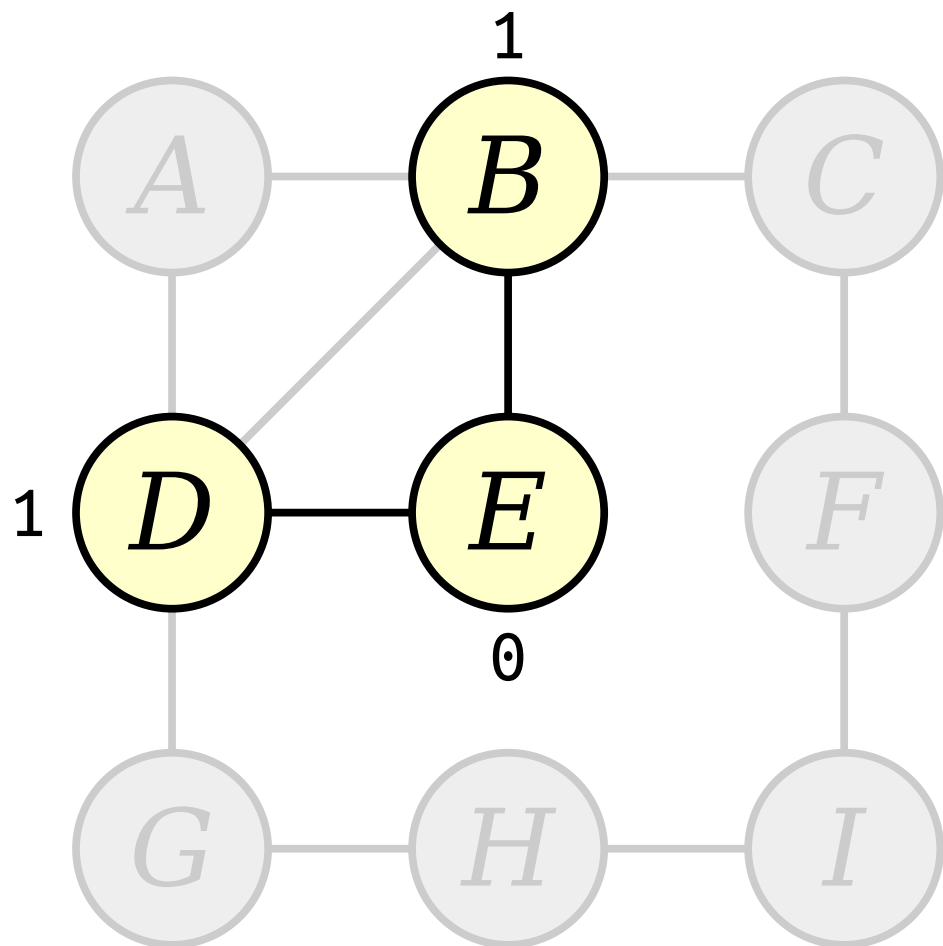


Visit nodes in ascending order of distance from the start node *E*.

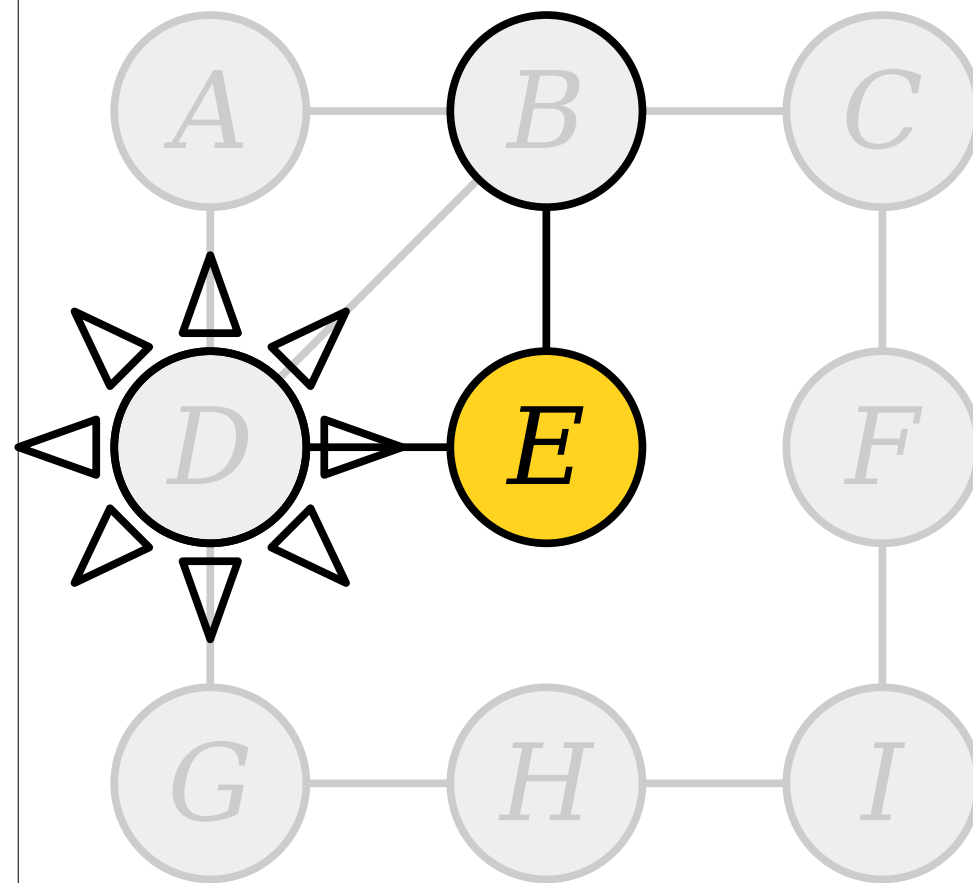


Queue: *D* *B*

Load newly-discovered nodes into a queue.

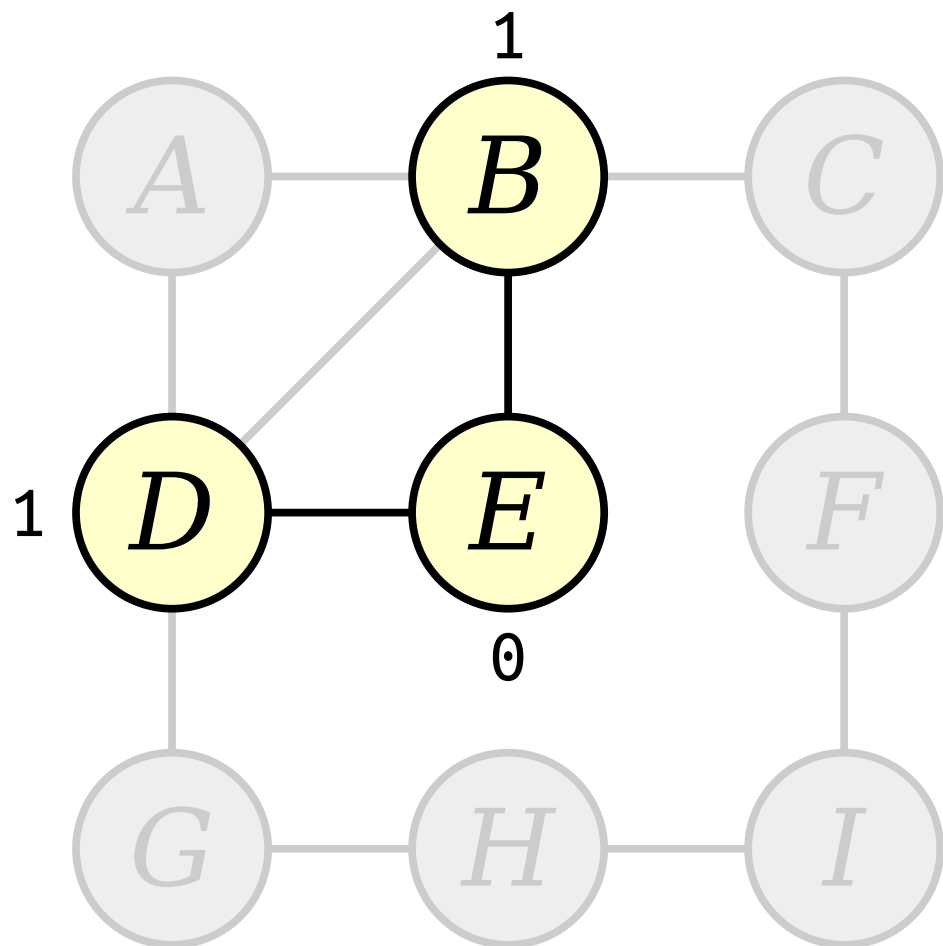


Visit nodes in ascending order of distance from the start node *E*.

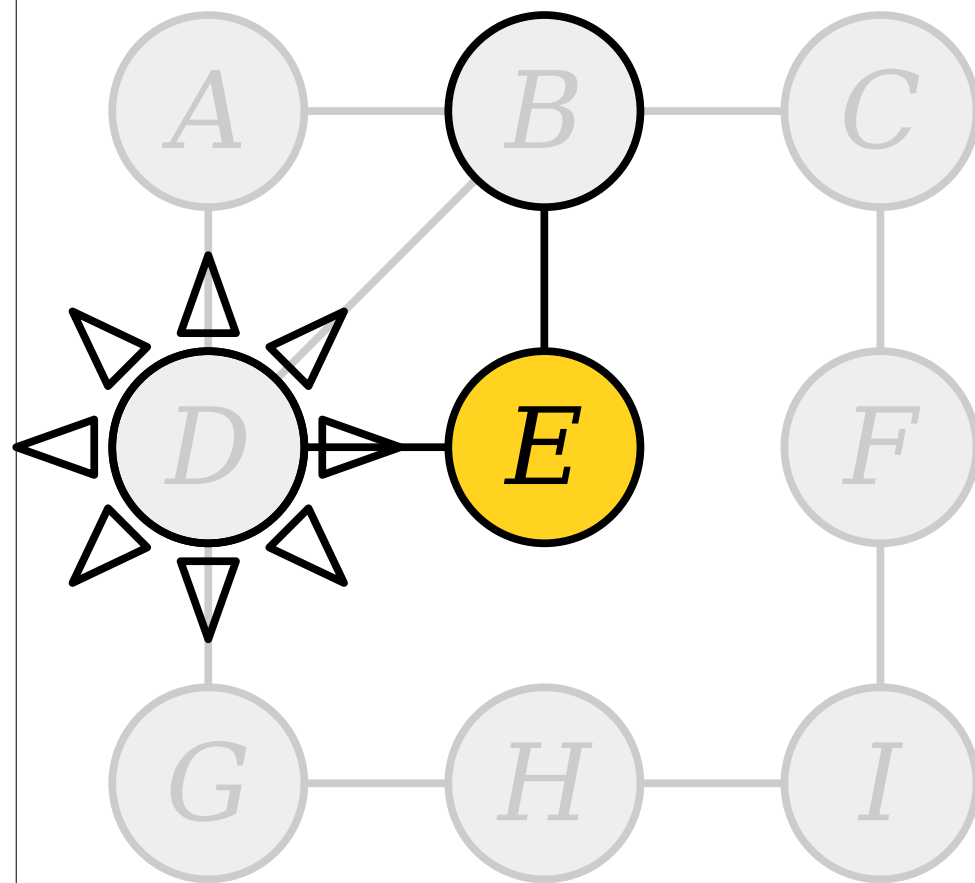


Queue: 

Load newly-discovered nodes into a queue.

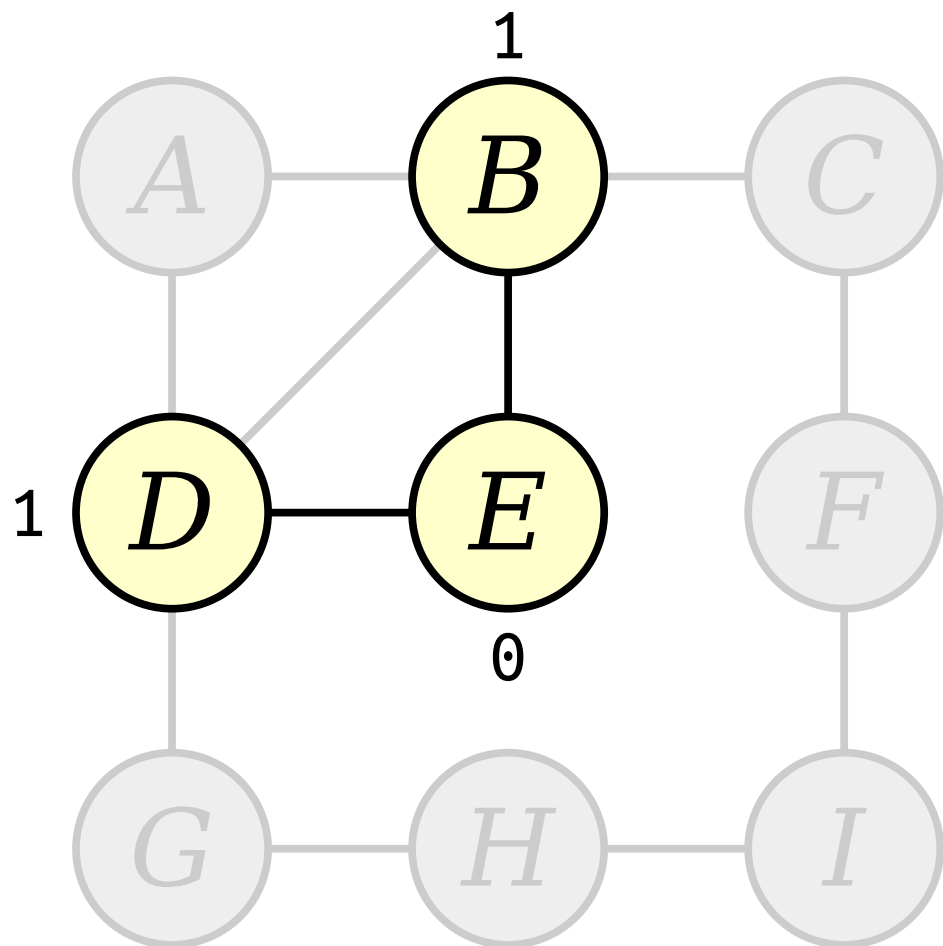


Visit nodes in ascending order of distance from the start node *E*.

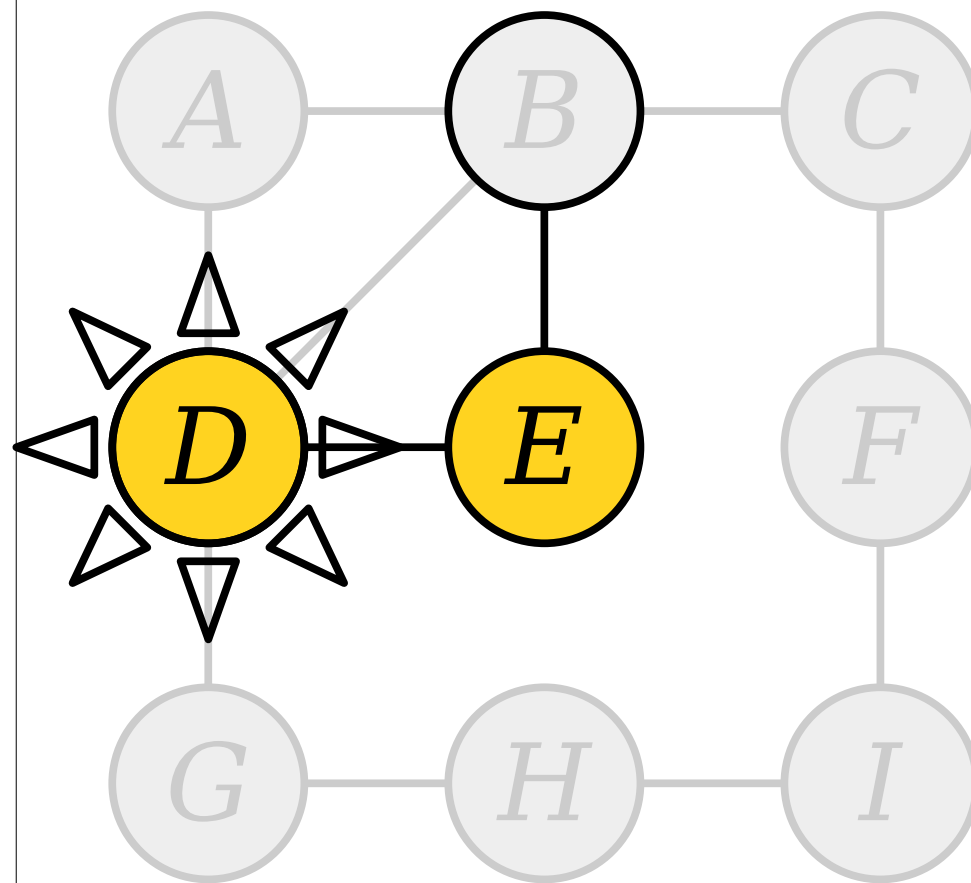


Queue: *B*

Load newly-discovered nodes into a queue.

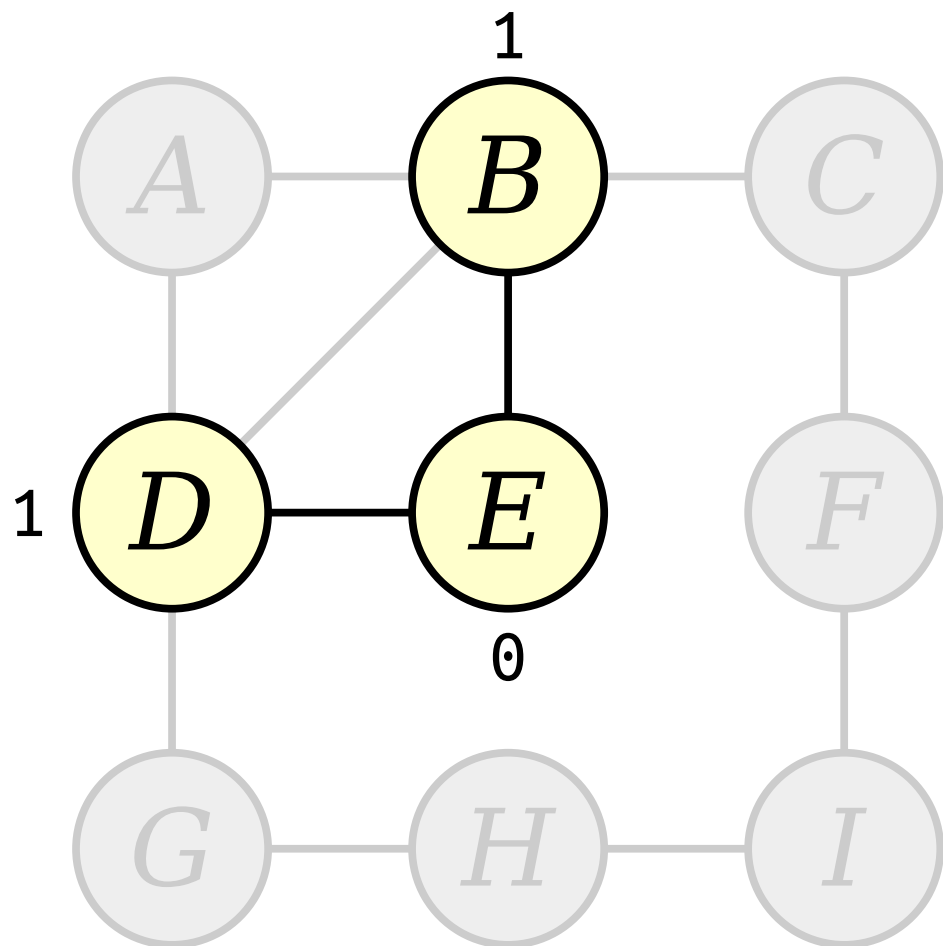


Visit nodes in ascending order of distance from the start node *E*.

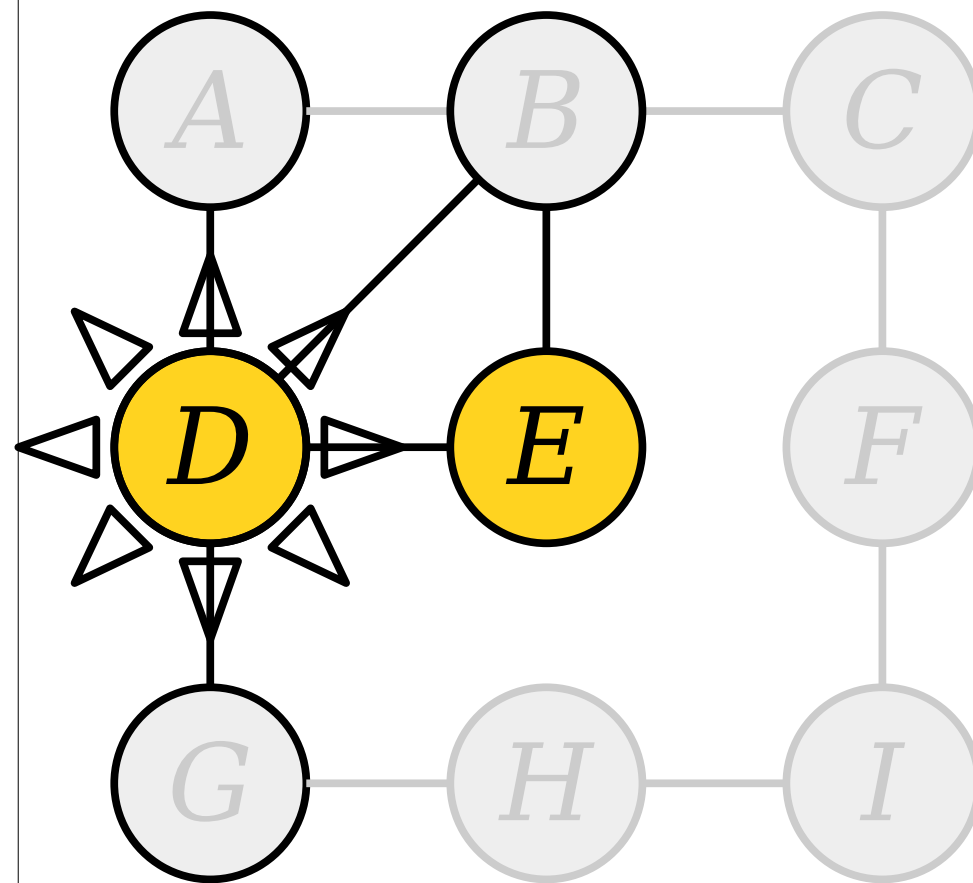


Queue: *B*

Load newly-discovered nodes into a queue.

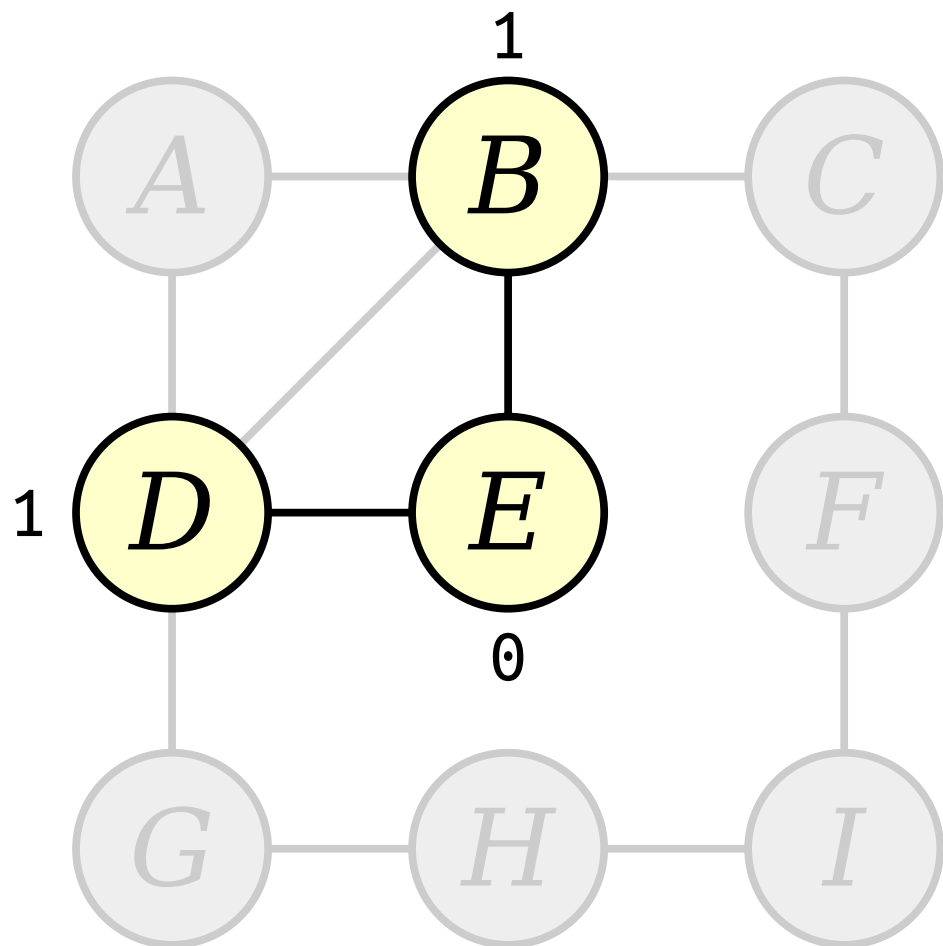


Visit nodes in ascending order of distance from the start node E .

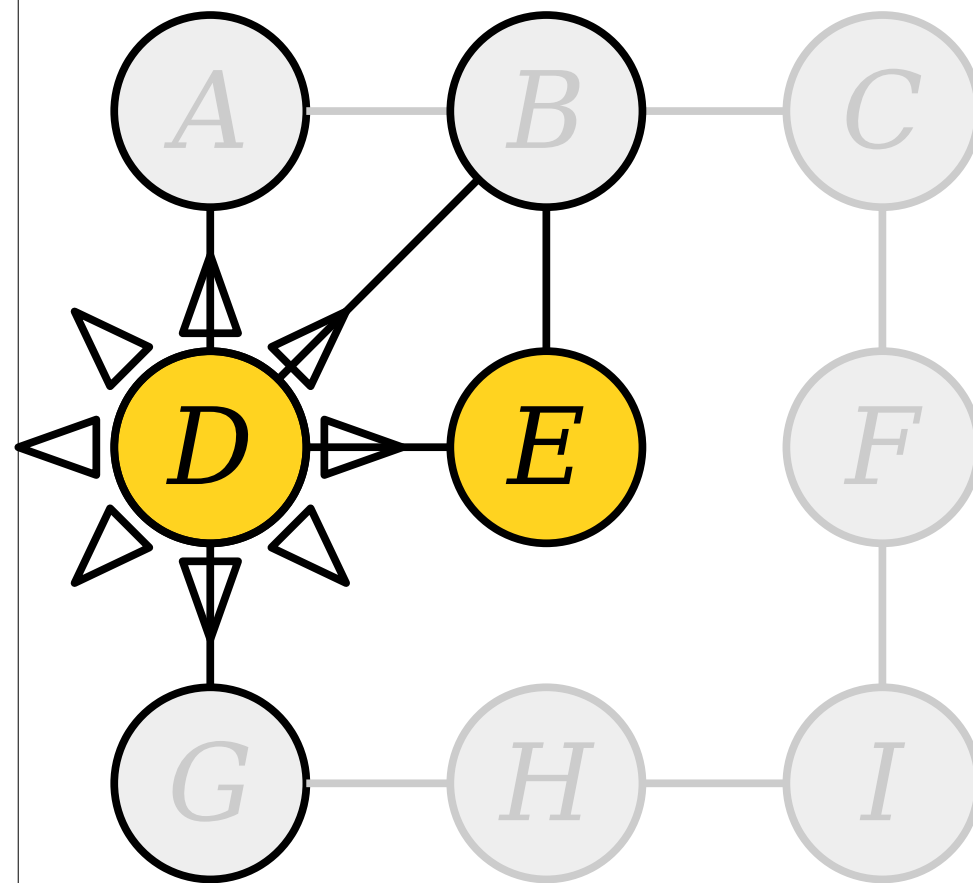


Queue: B

Load newly-discovered nodes into a queue.

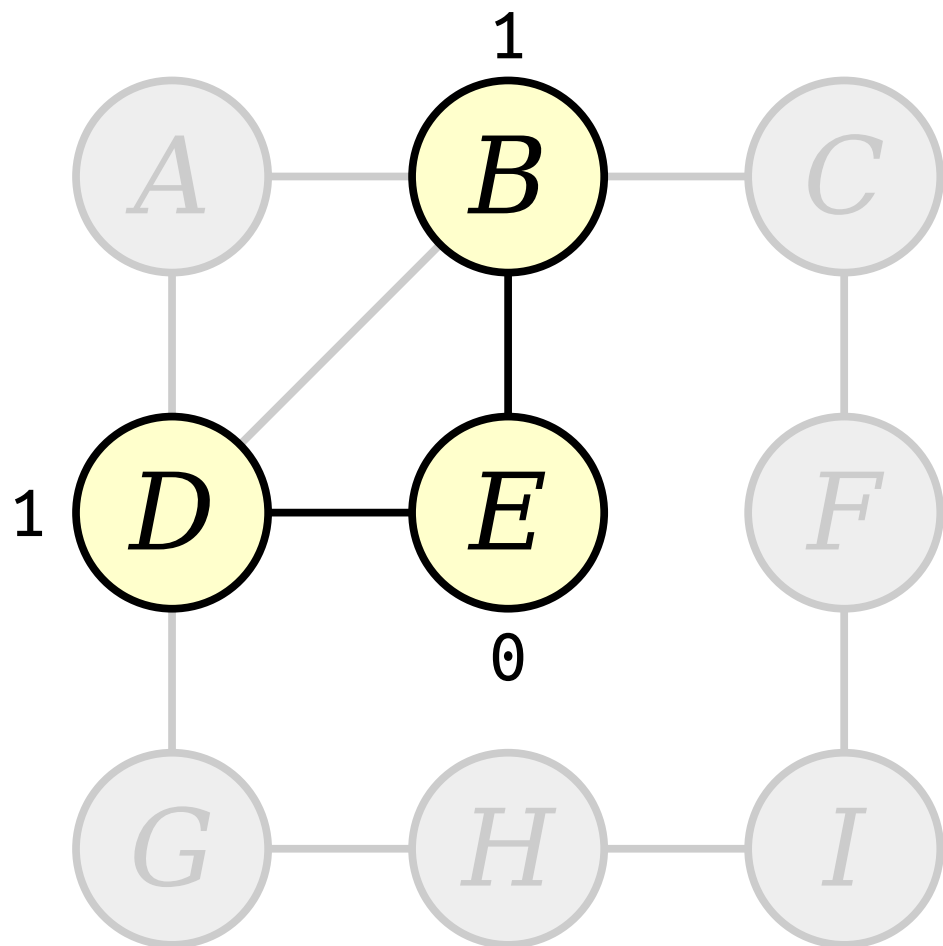


Visit nodes in ascending order of distance from the start node *E*.

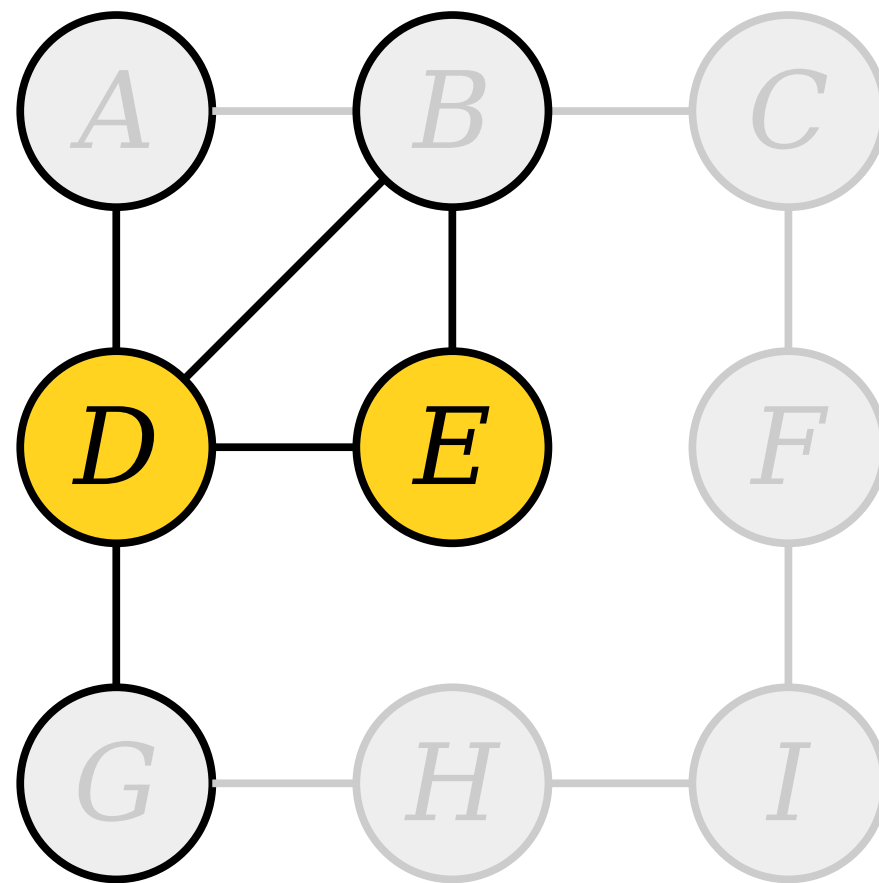


Queue: *B* *A* *G*

Load newly-discovered nodes into a queue.

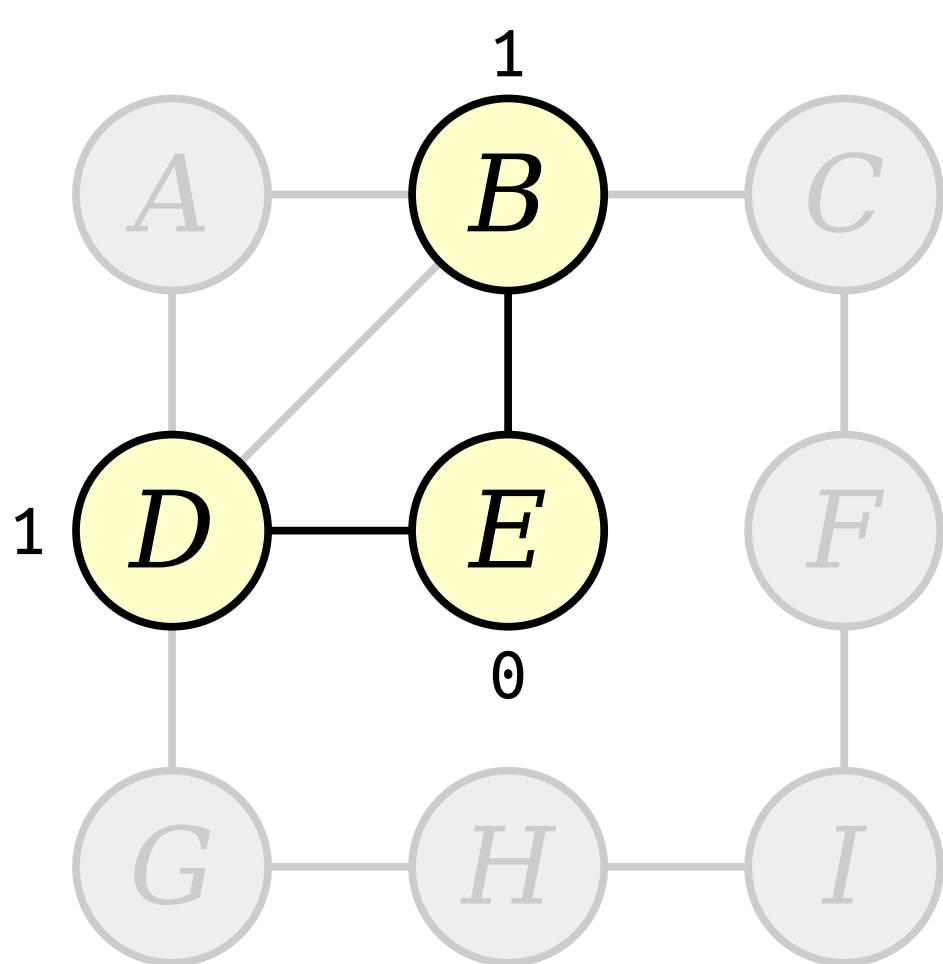


Visit nodes in ascending order of distance from the start node *E*.

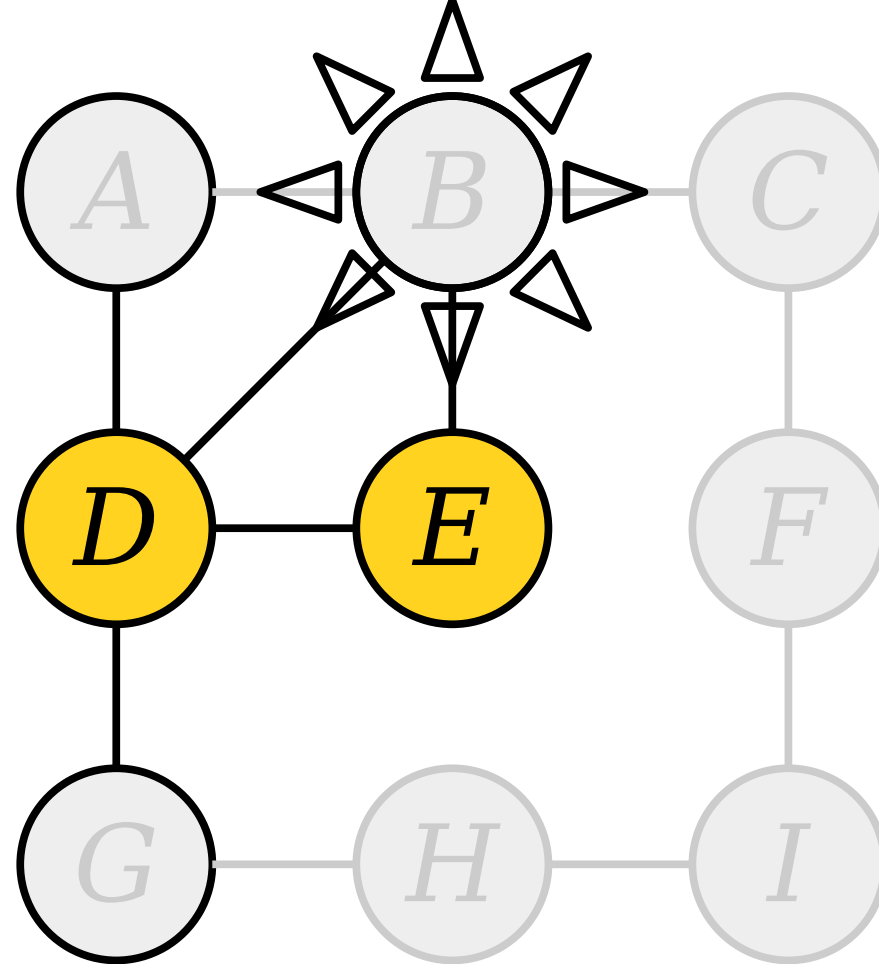


Queue: *B* *A* *G*

Load newly-discovered nodes into a queue.

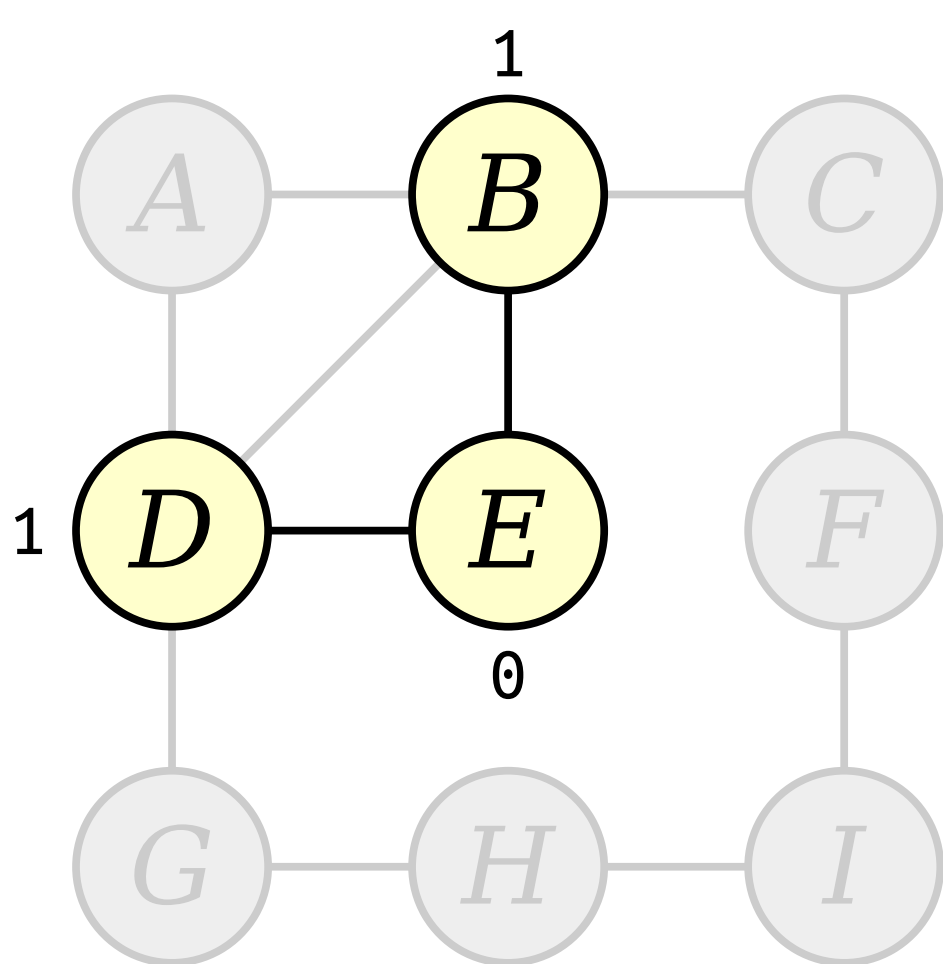


Visit nodes in ascending order of distance from the start node *E*.

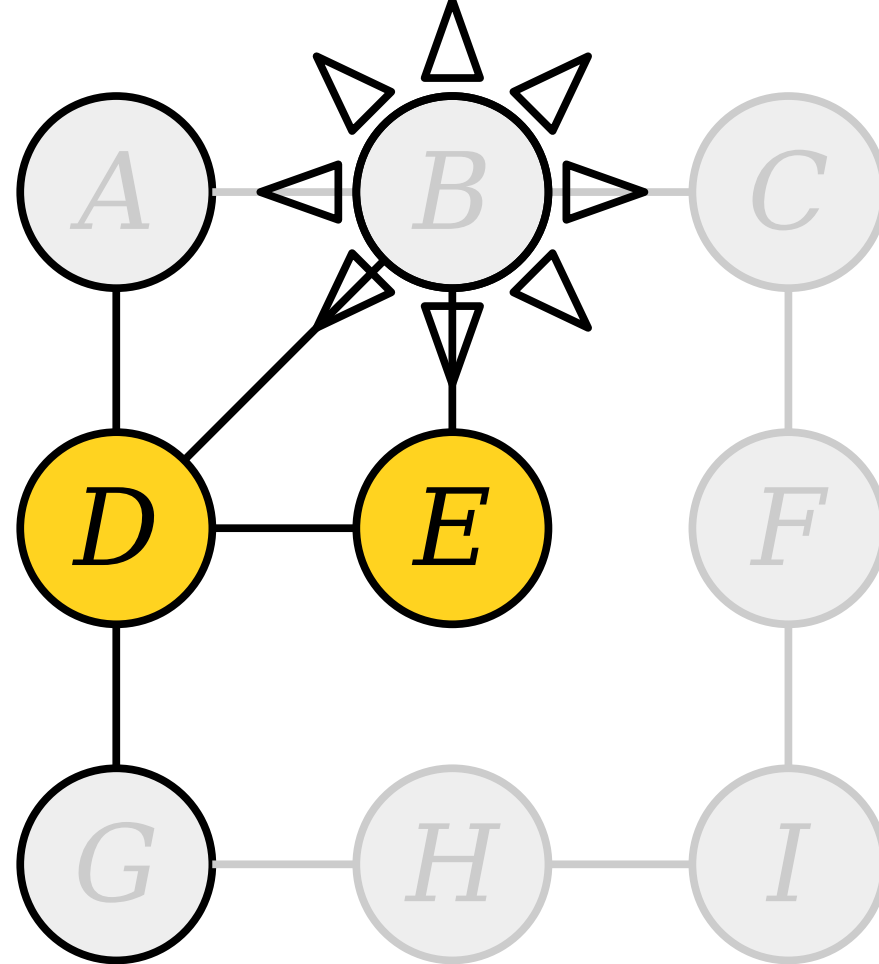


Queue: *B* *A* *G*

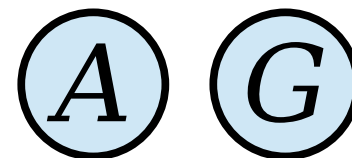
Load newly-discovered nodes into a queue.



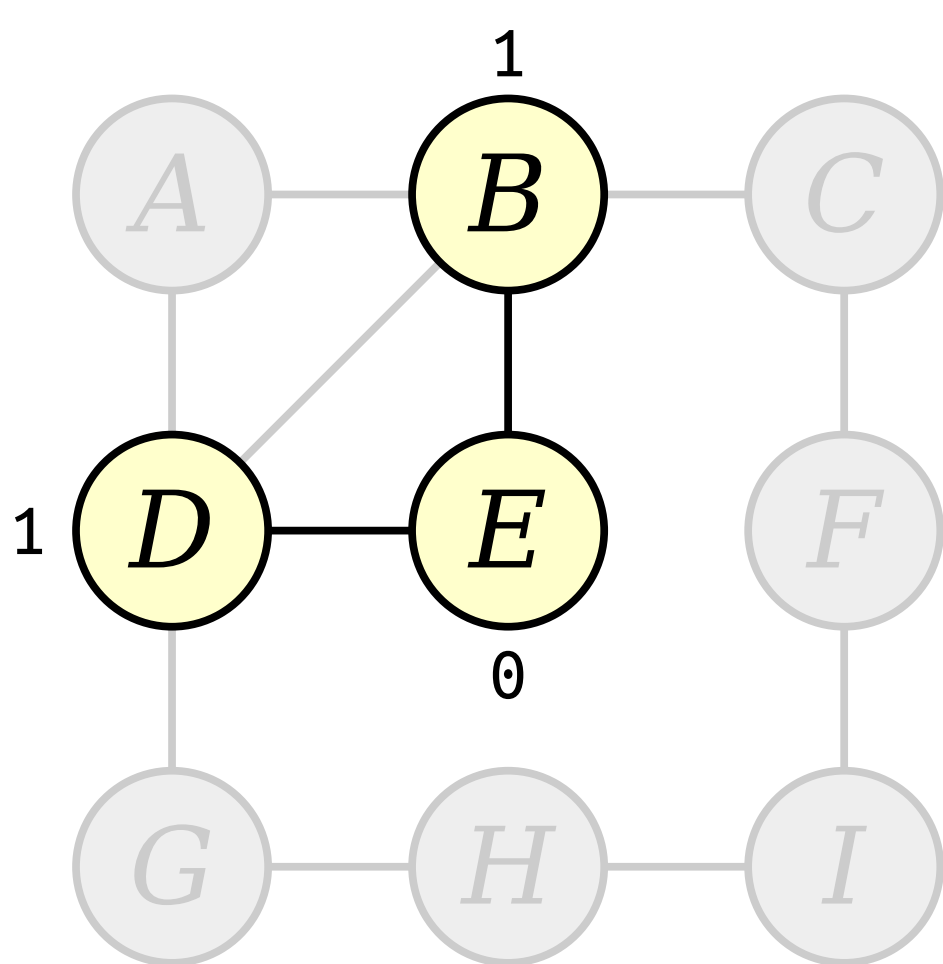
Visit nodes in ascending order of distance from the start node *E*.



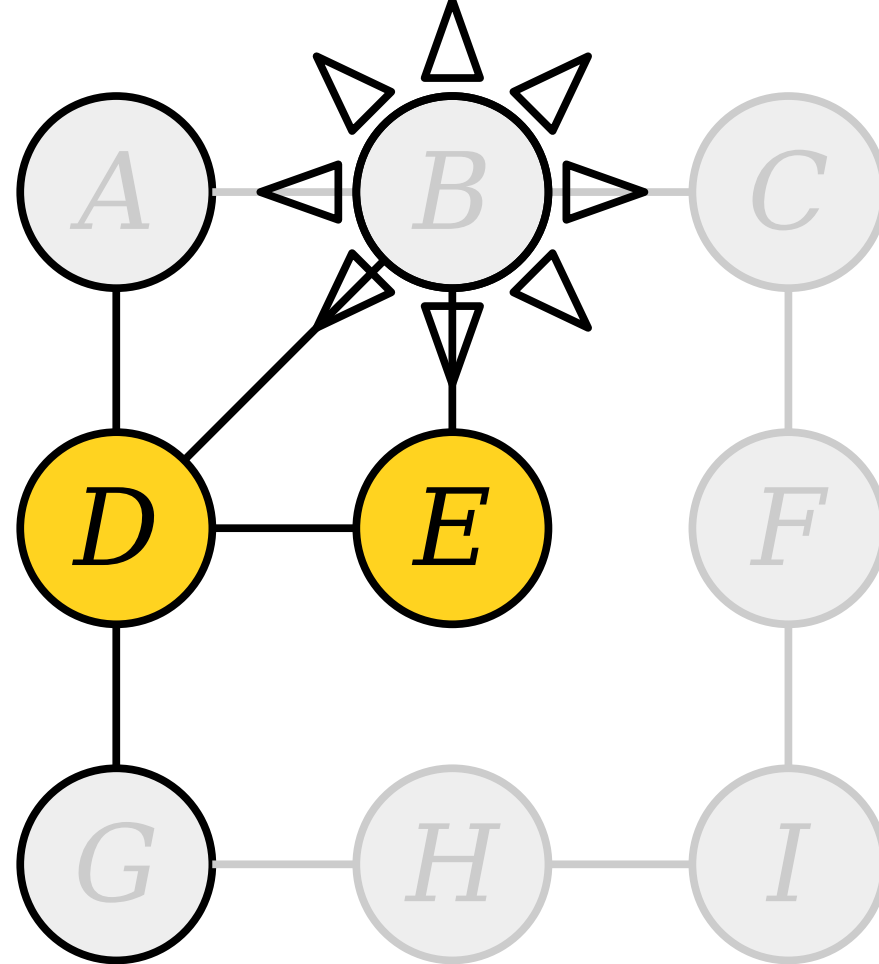
Queue:



Load newly-discovered nodes into a queue.

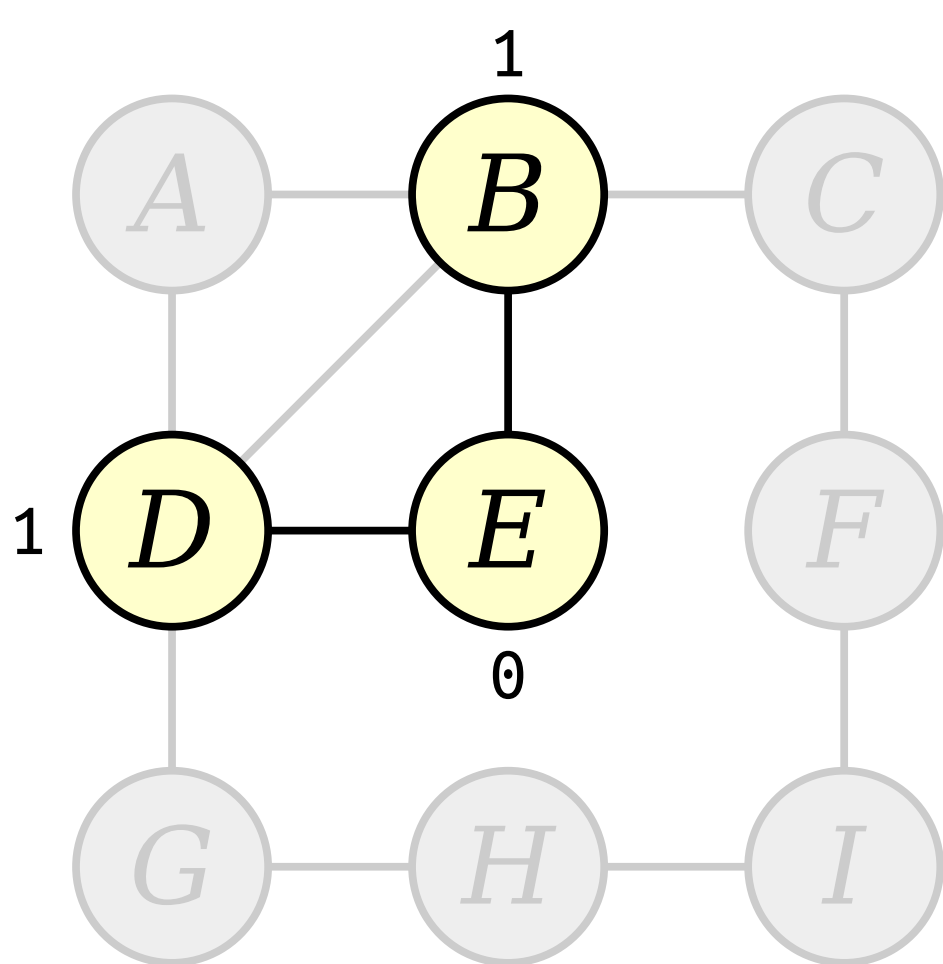


Visit nodes in ascending order of distance from the start node *E*.

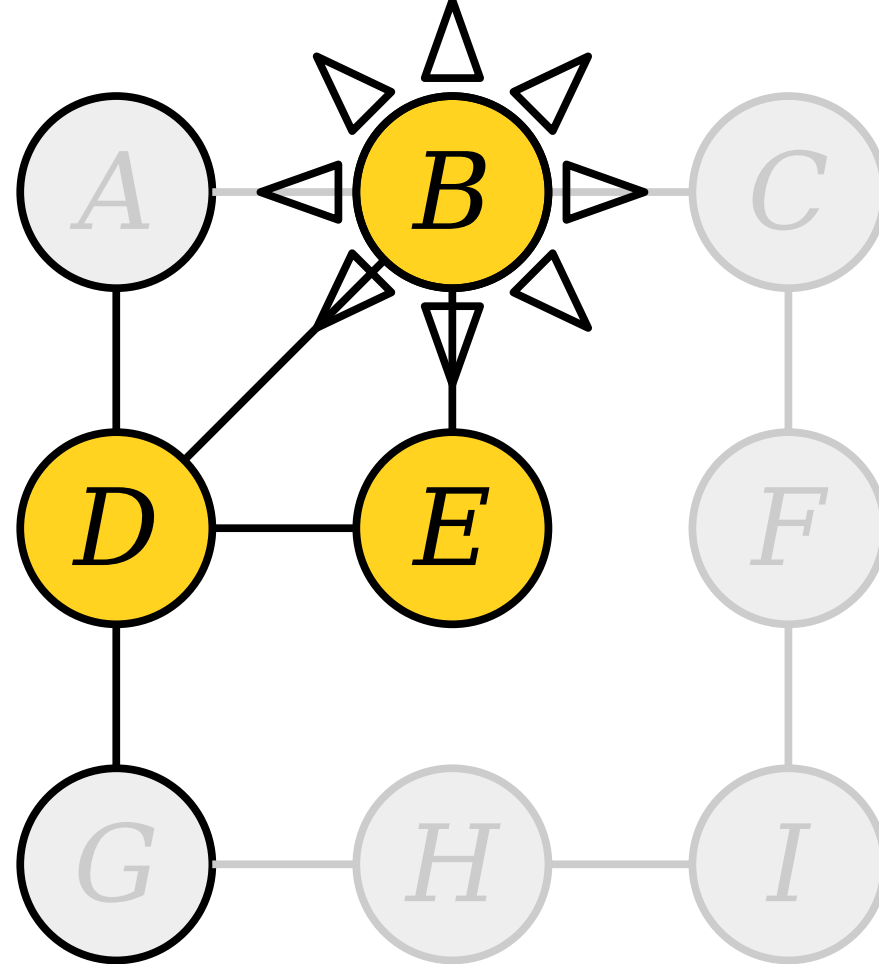


Queue: *A* *G*

Load newly-discovered nodes into a queue.

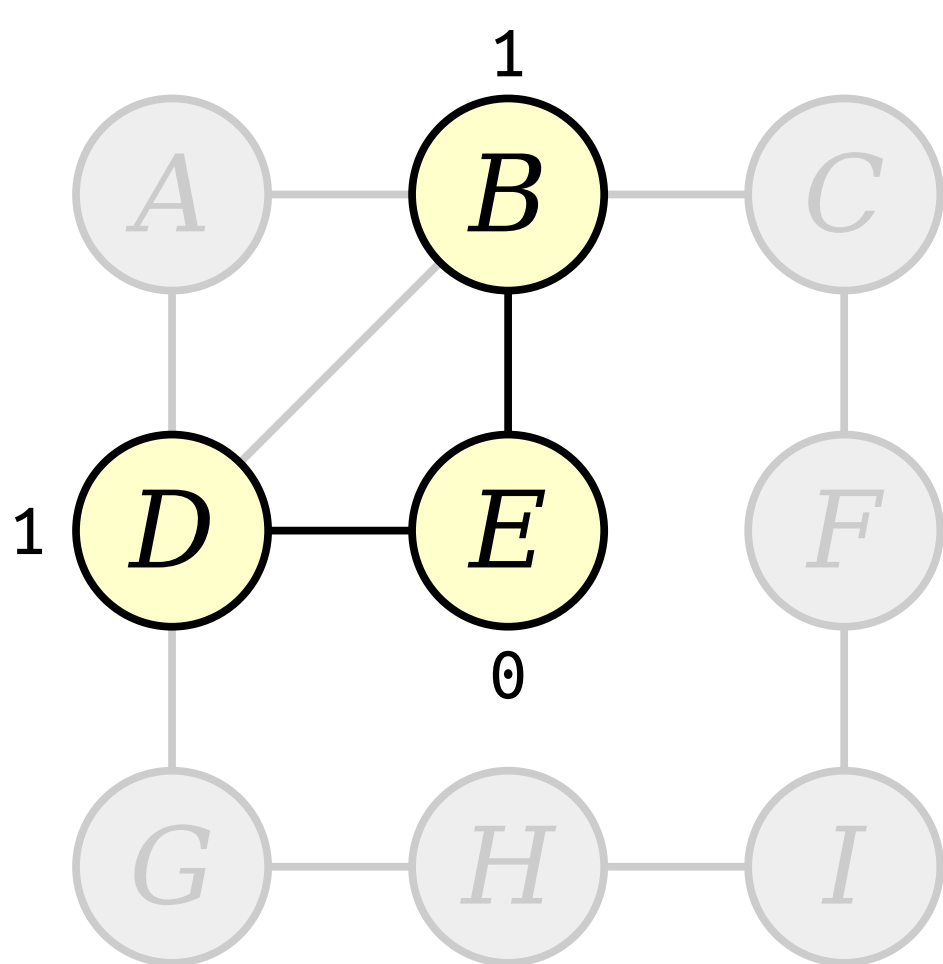


Visit nodes in ascending order of distance from the start node *E*.

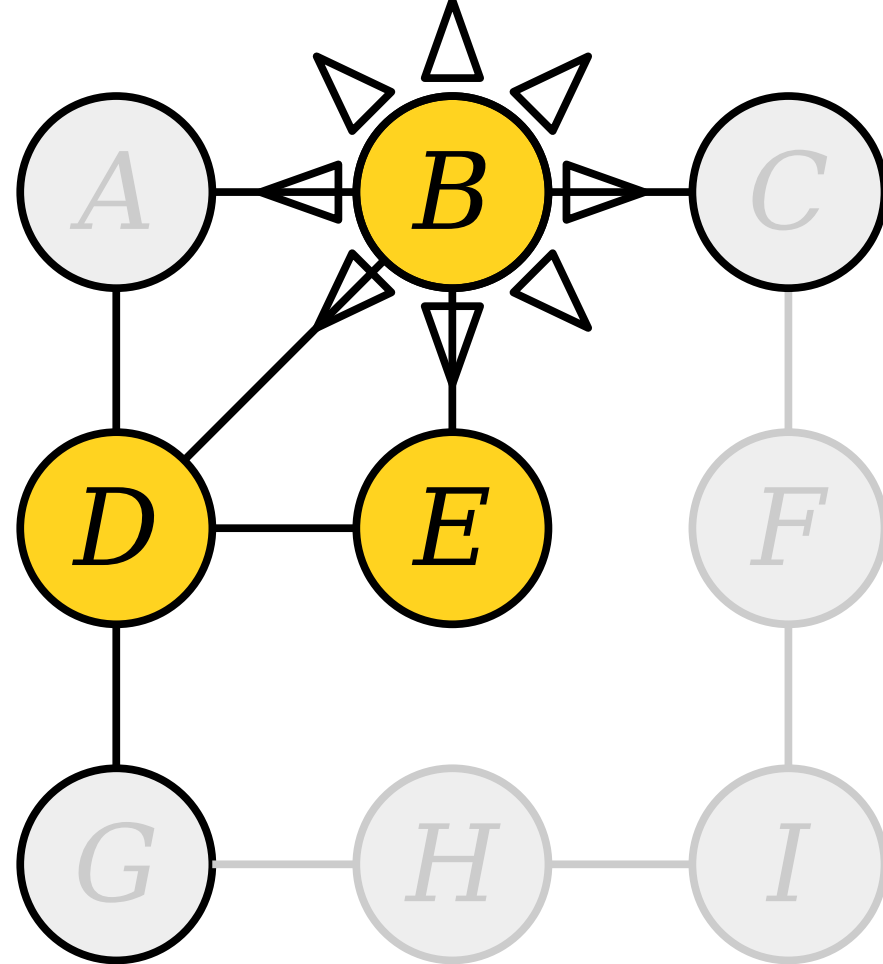


Queue: *A* *G*

Load newly-discovered nodes into a queue.

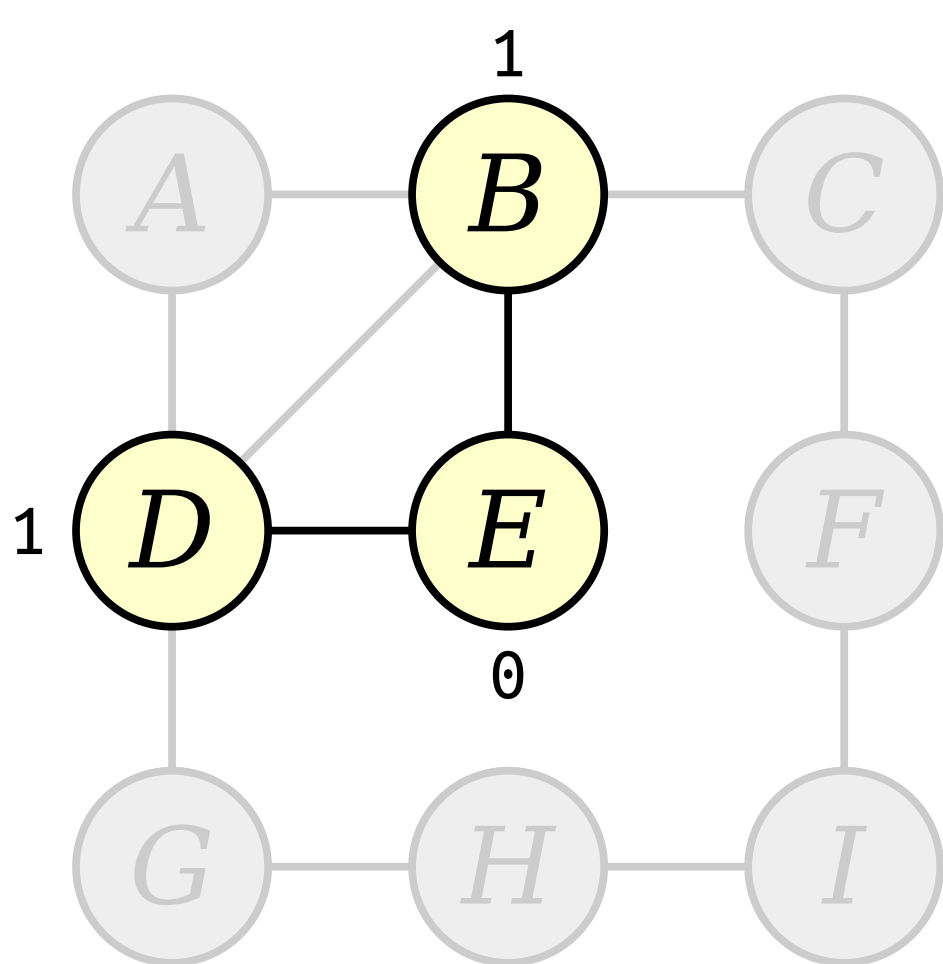


Visit nodes in ascending order of distance from the start node *E*.

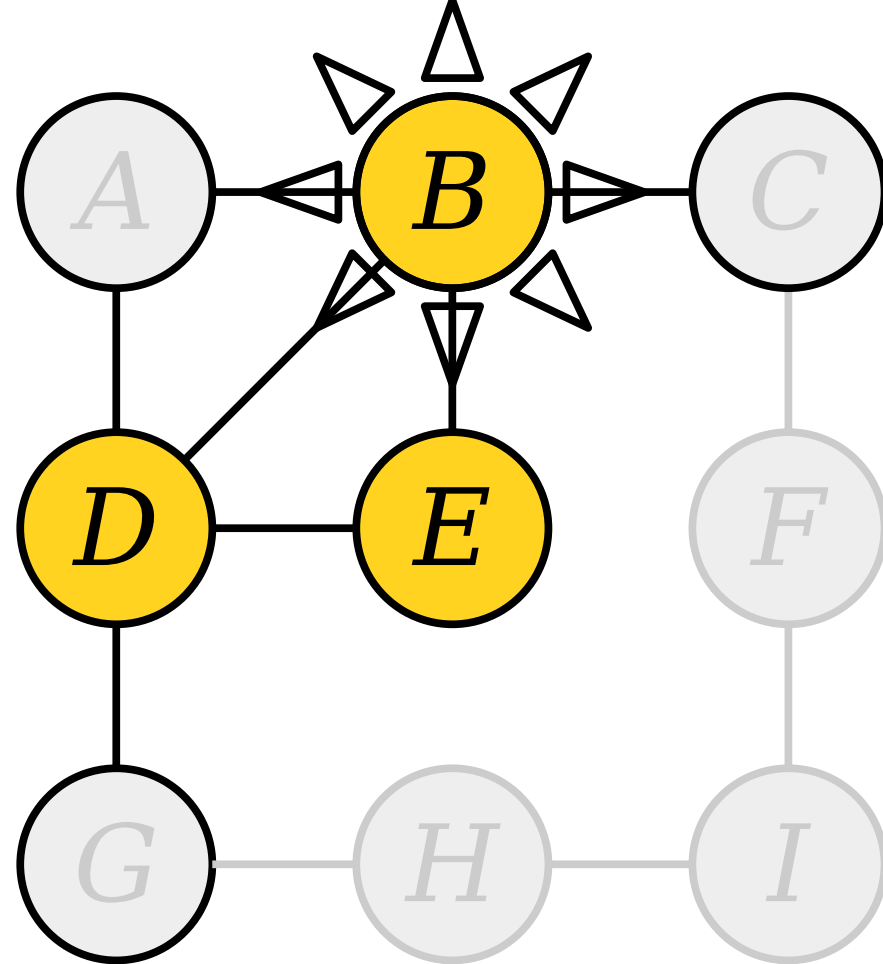


Queue: *A* *G*

Load newly-discovered nodes into a queue.

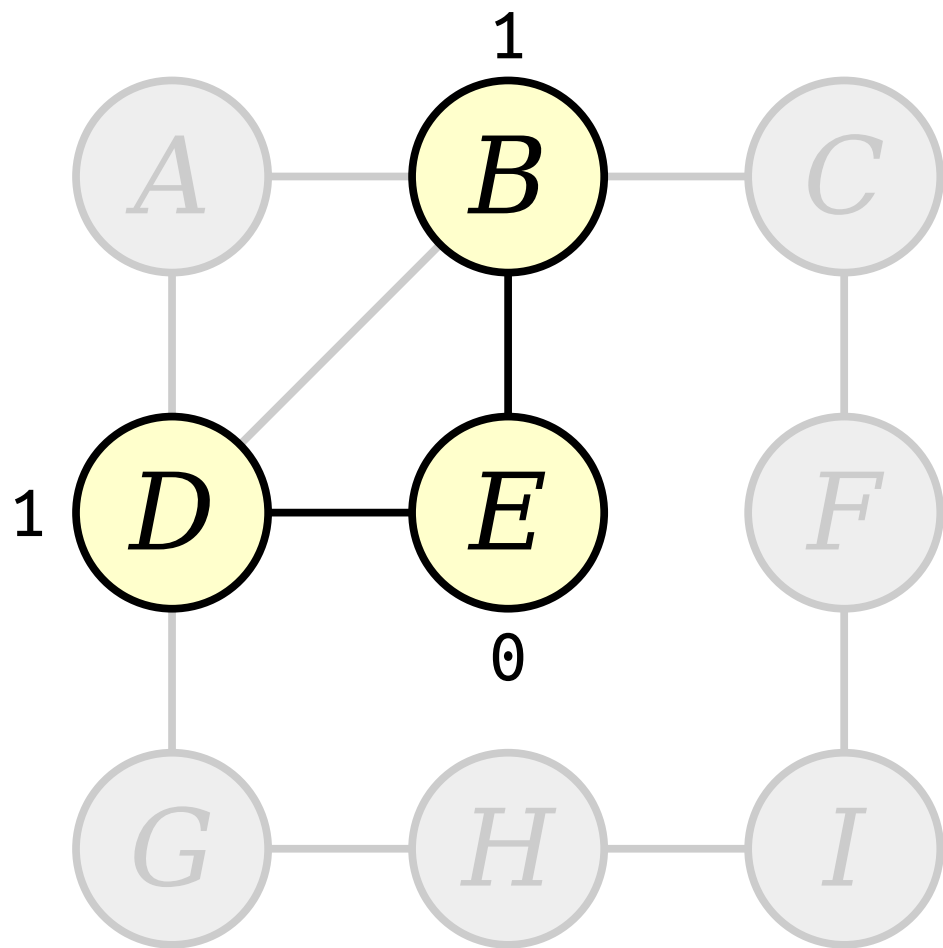


Visit nodes in ascending order of distance from the start node *E*.

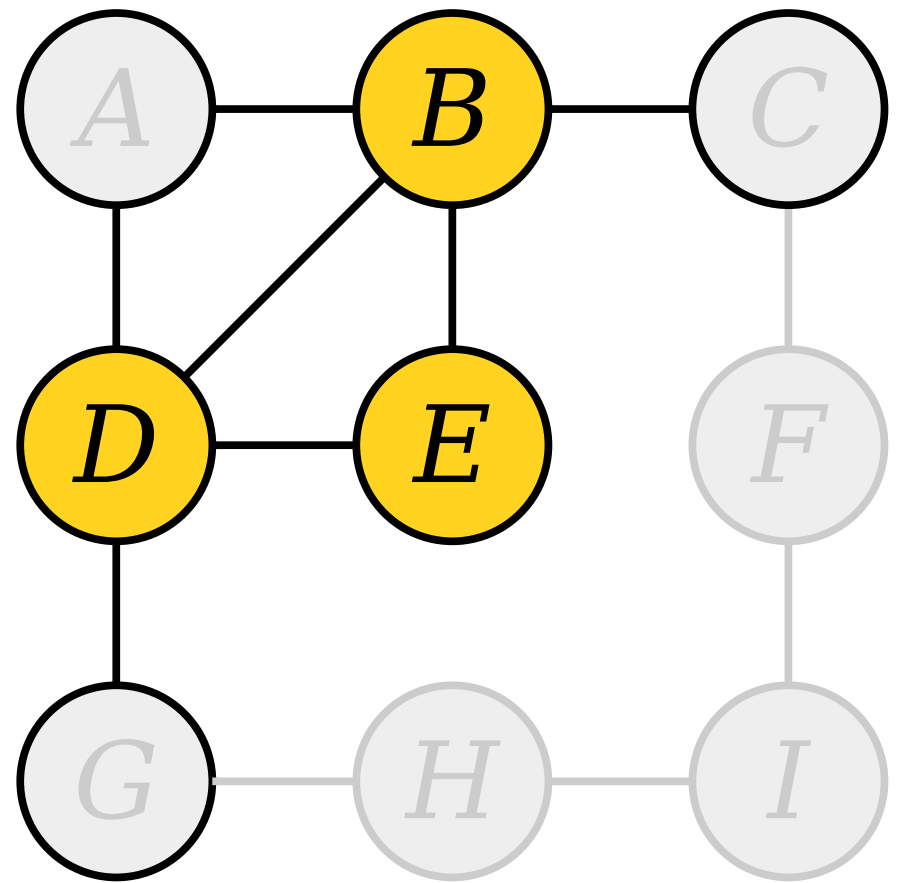


Queue: *A* *G* *C*

Load newly-discovered nodes into a queue.

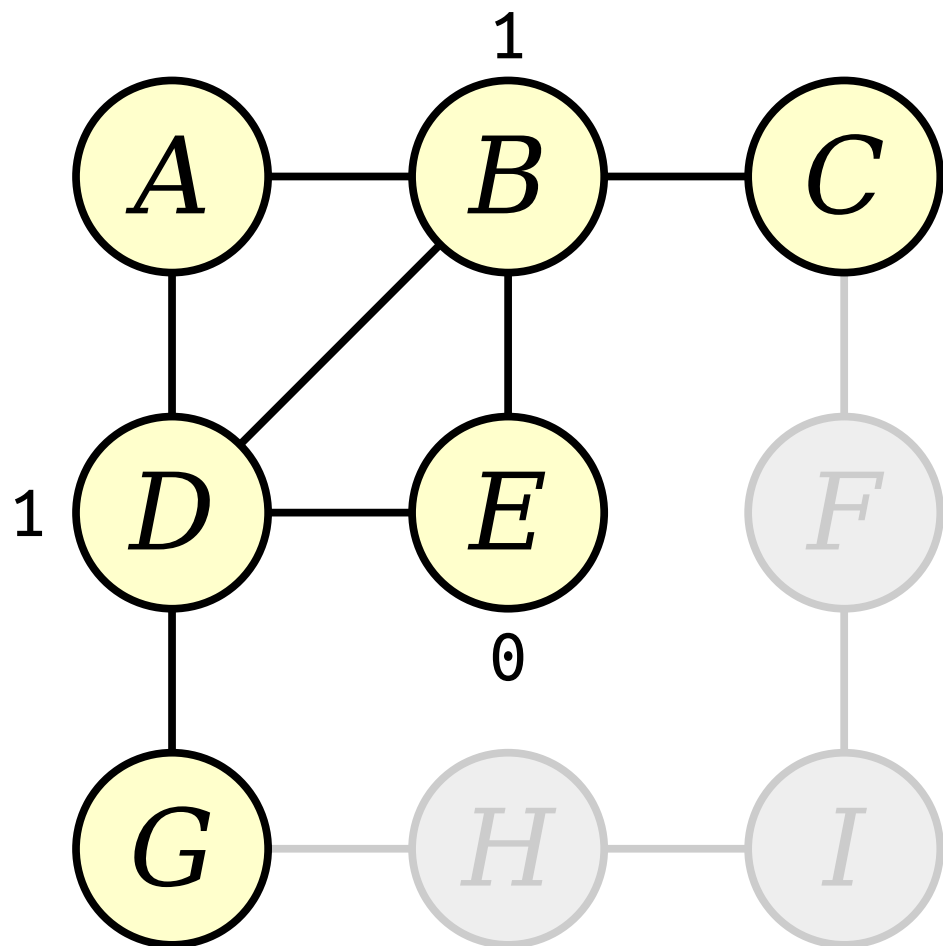


Visit nodes in ascending order of distance from the start node *E*.

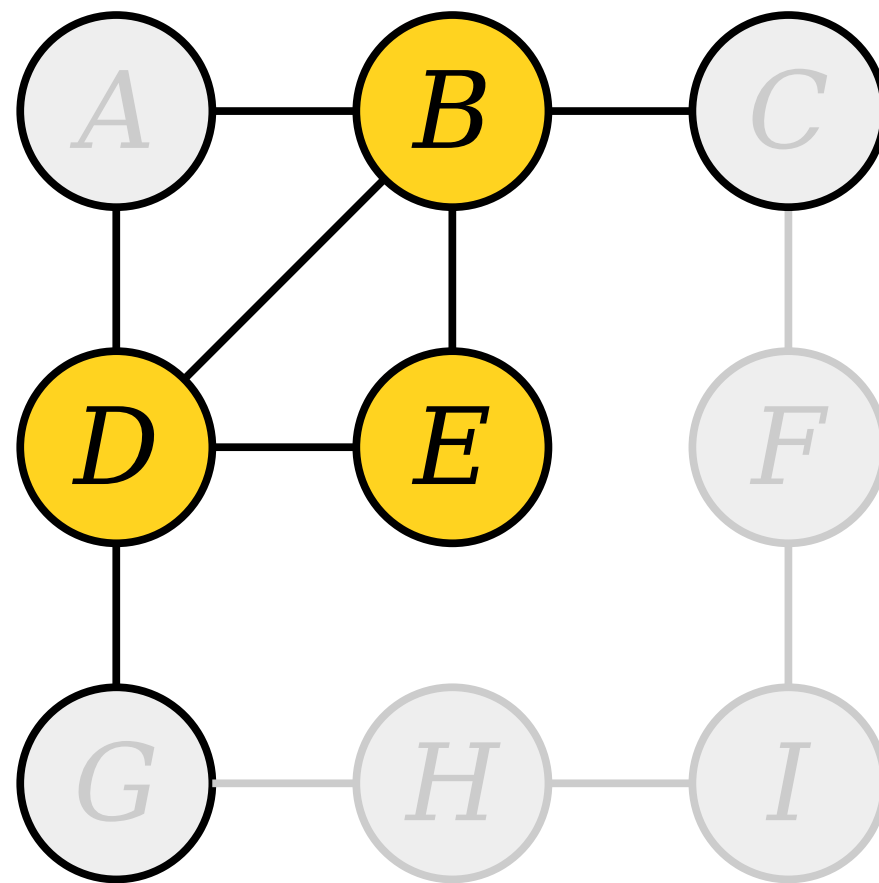


Queue: *A* *G* *C*

Load newly-discovered nodes into a queue.

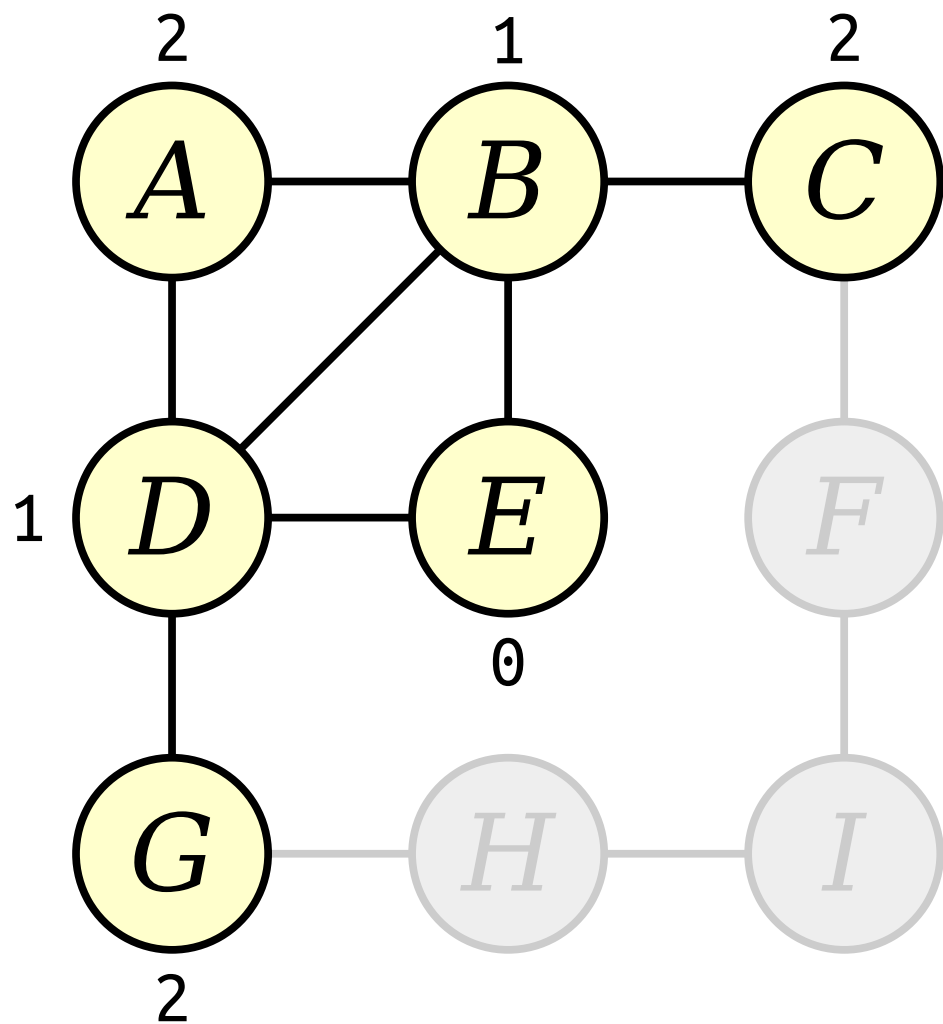


Visit nodes in ascending order of distance from the start node E .

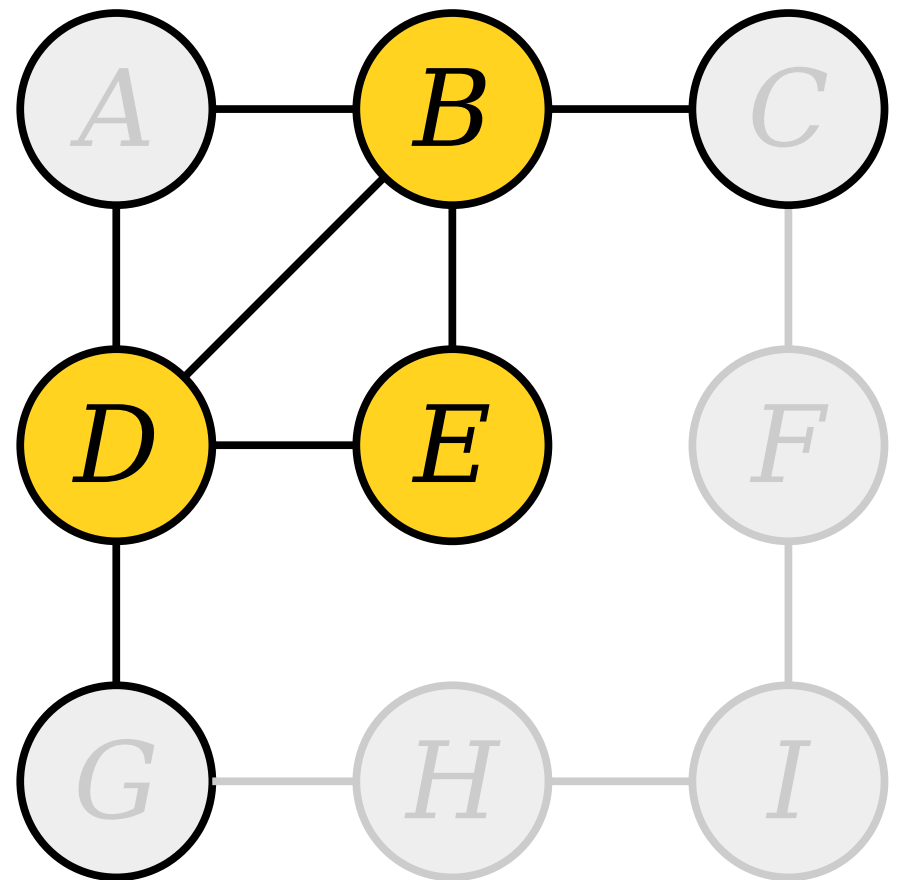


Queue: A G C

Load newly-discovered nodes into a queue.

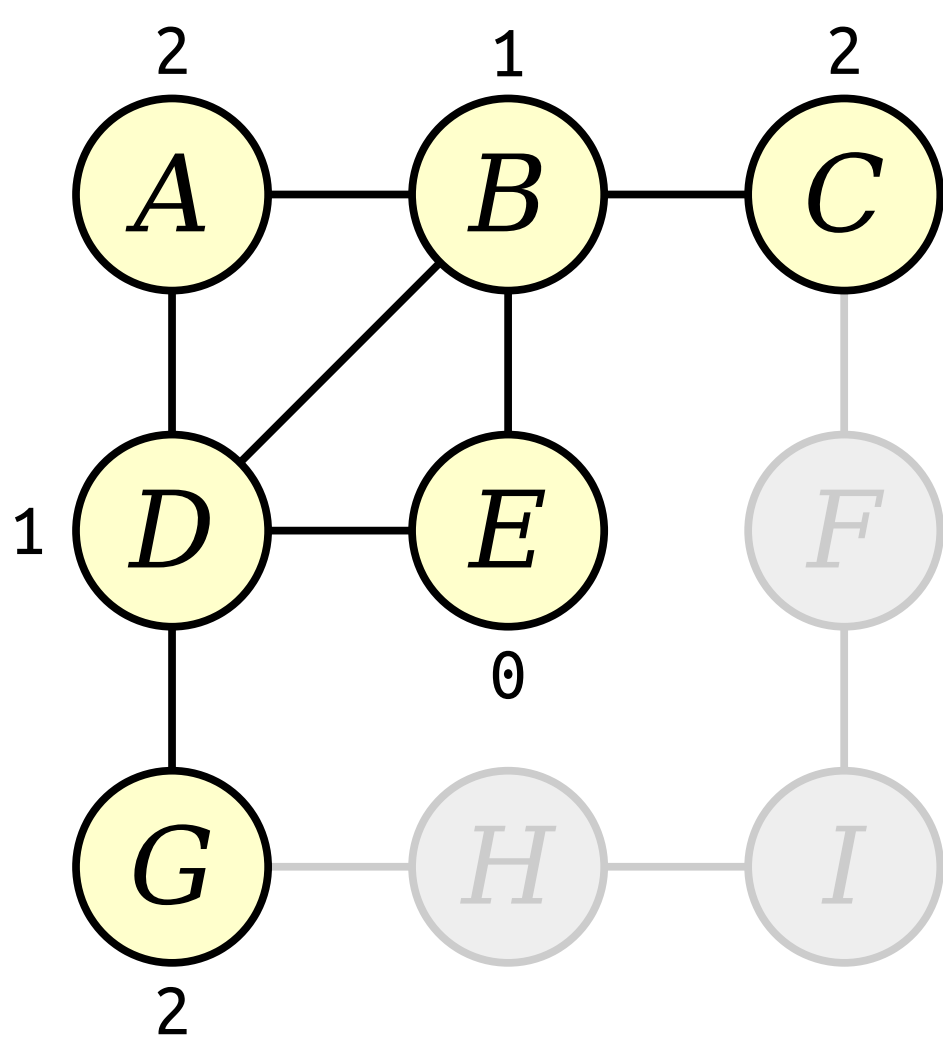


Visit nodes in ascending order of distance from the start node E .

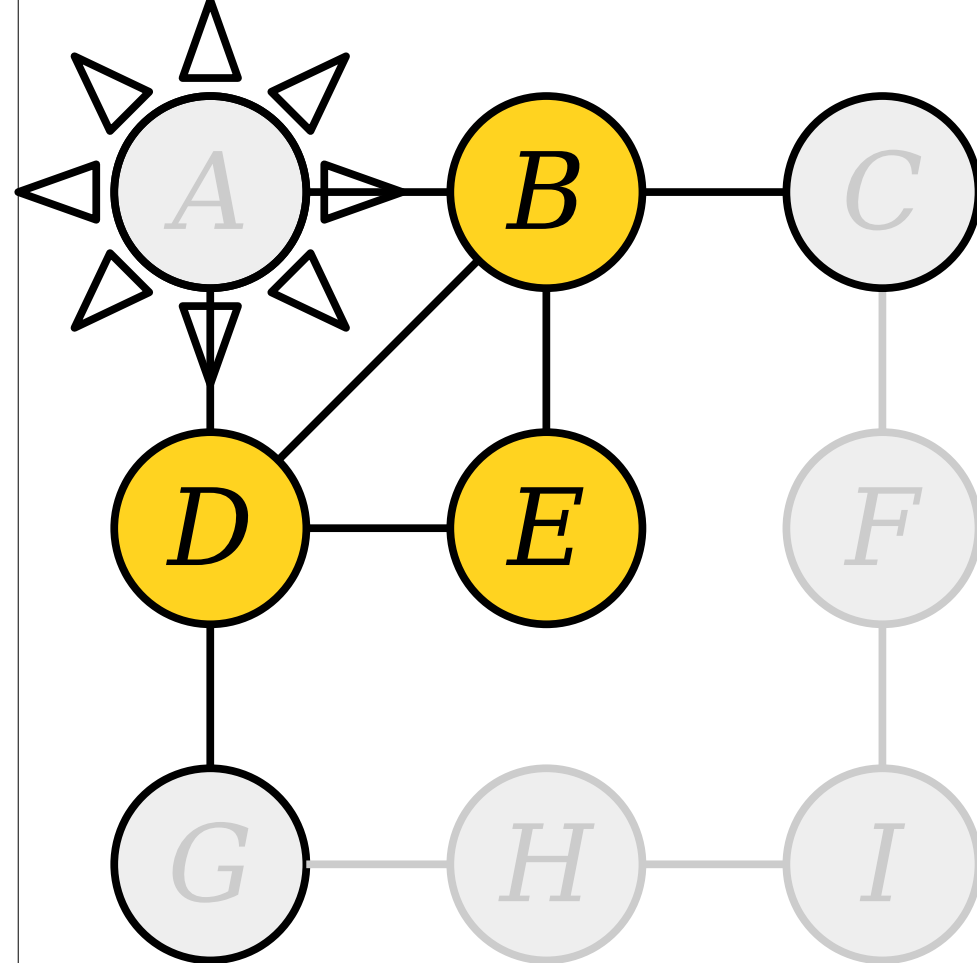


Queue: A G C

Load newly-discovered nodes into a queue.

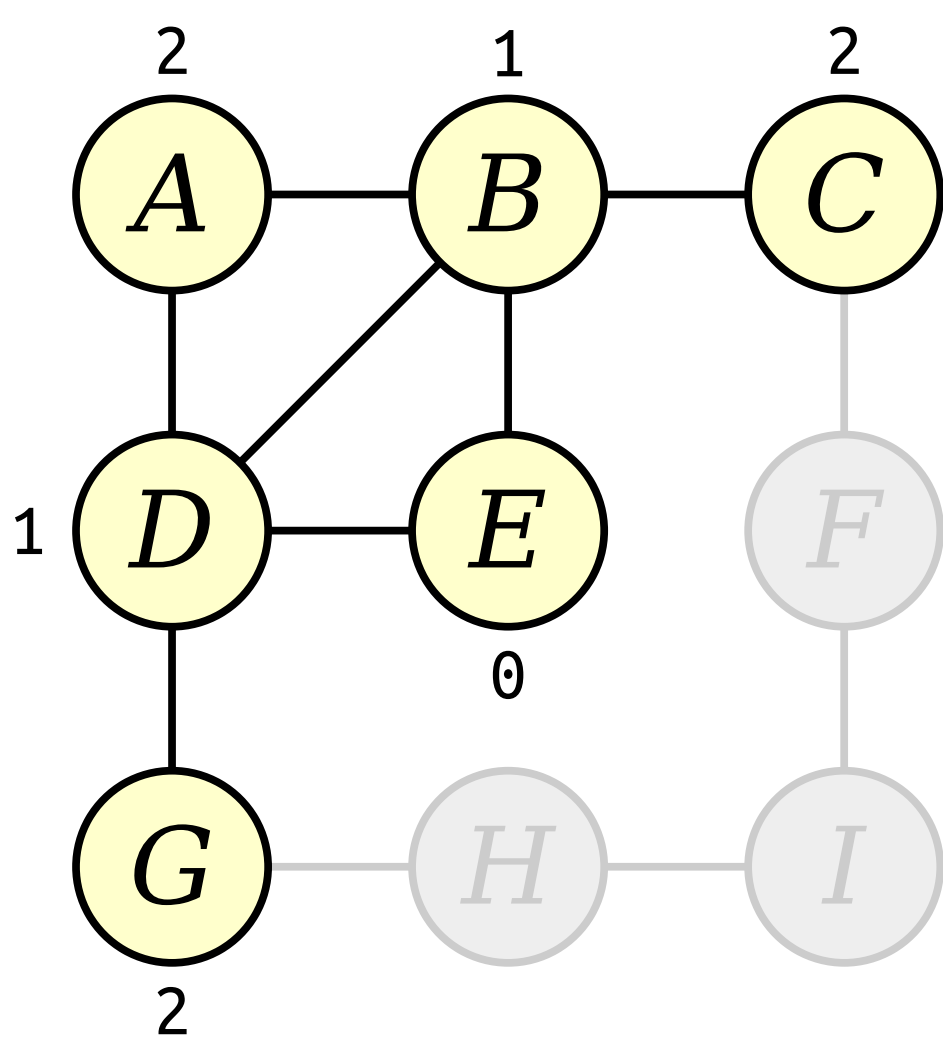


Visit nodes in ascending order of distance from the start node E .

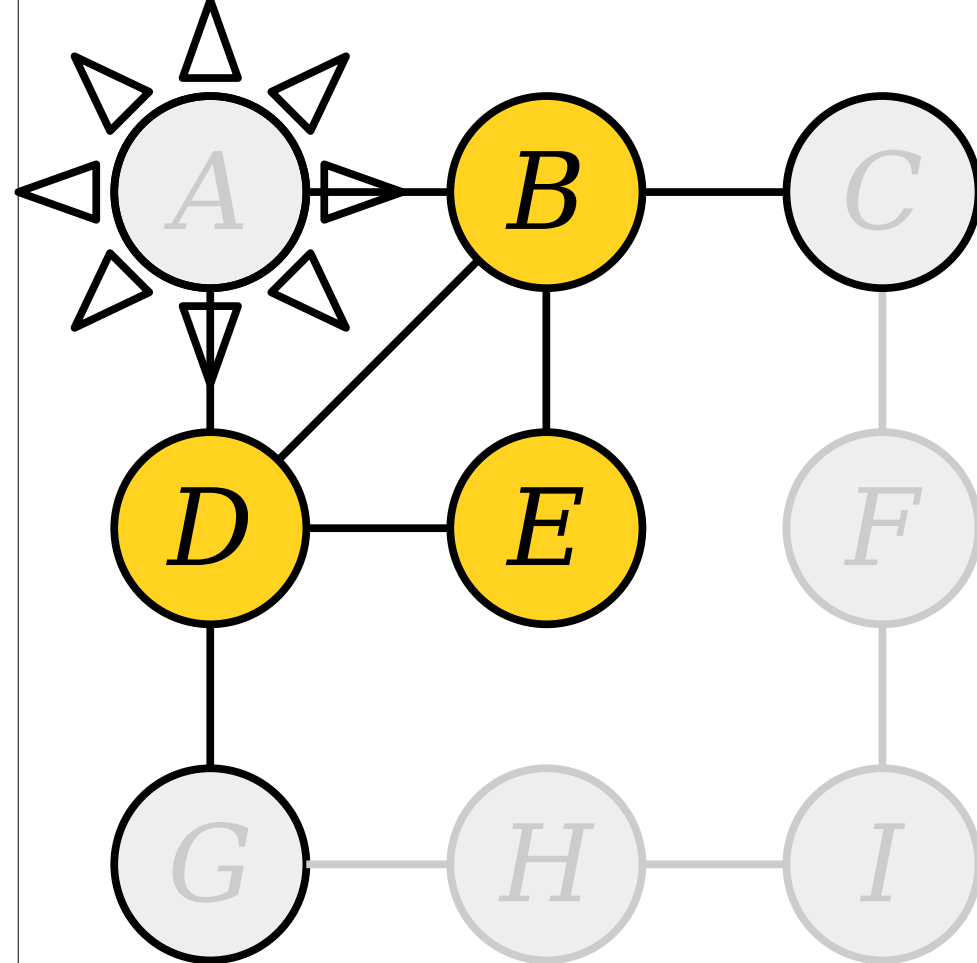


Queue: A G C

Load newly-discovered nodes into a queue.

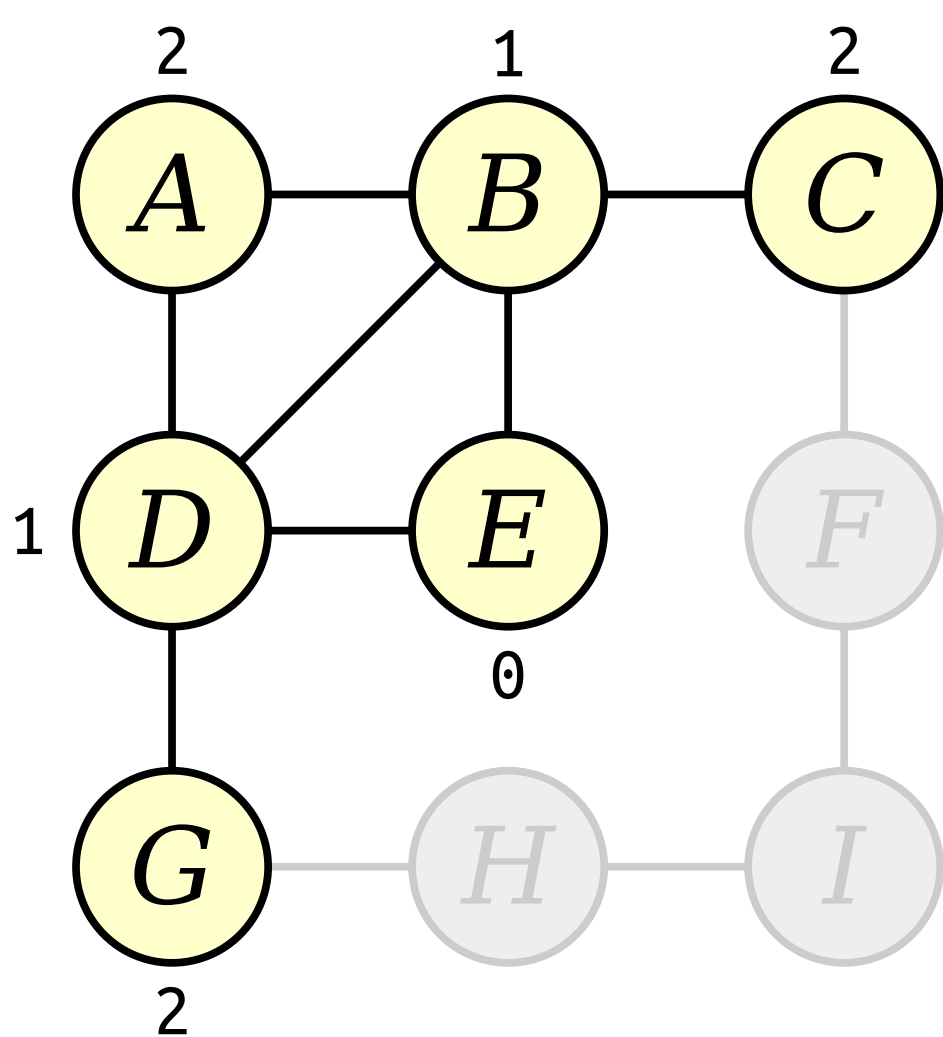


Visit nodes in ascending order of distance from the start node E .

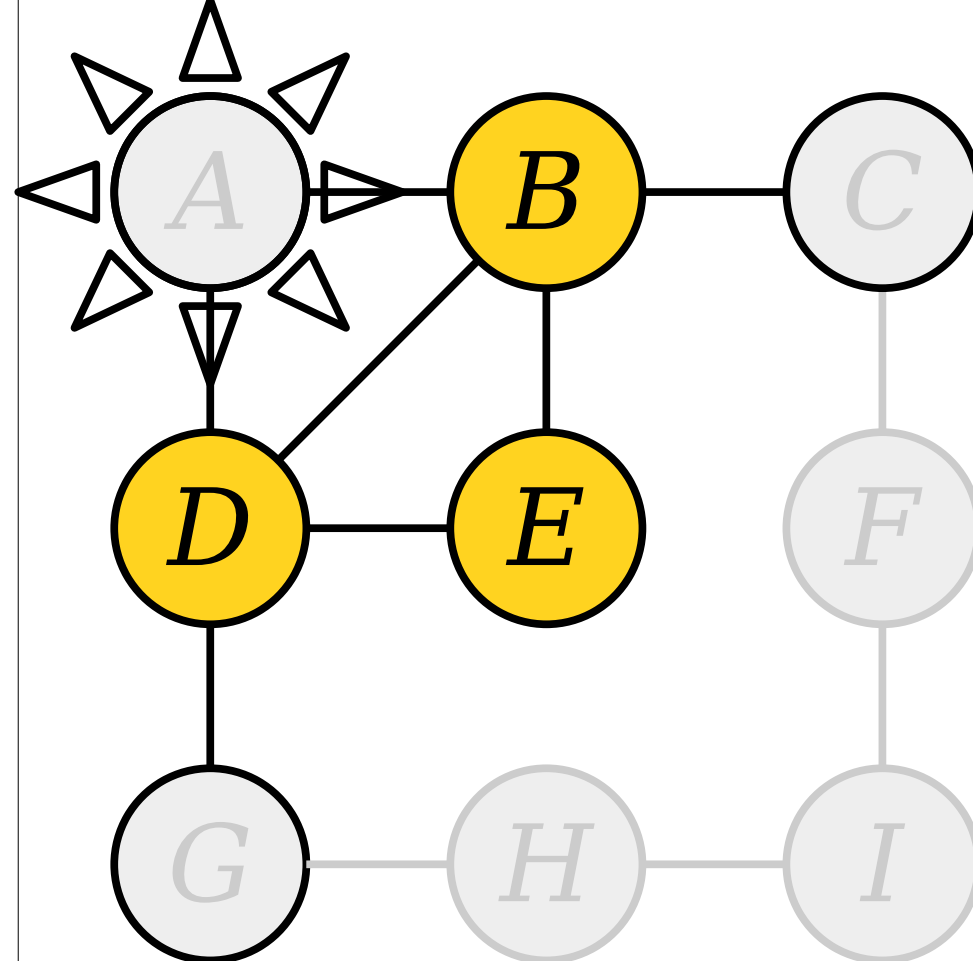


Queue: G C

Load newly-discovered nodes into a queue.

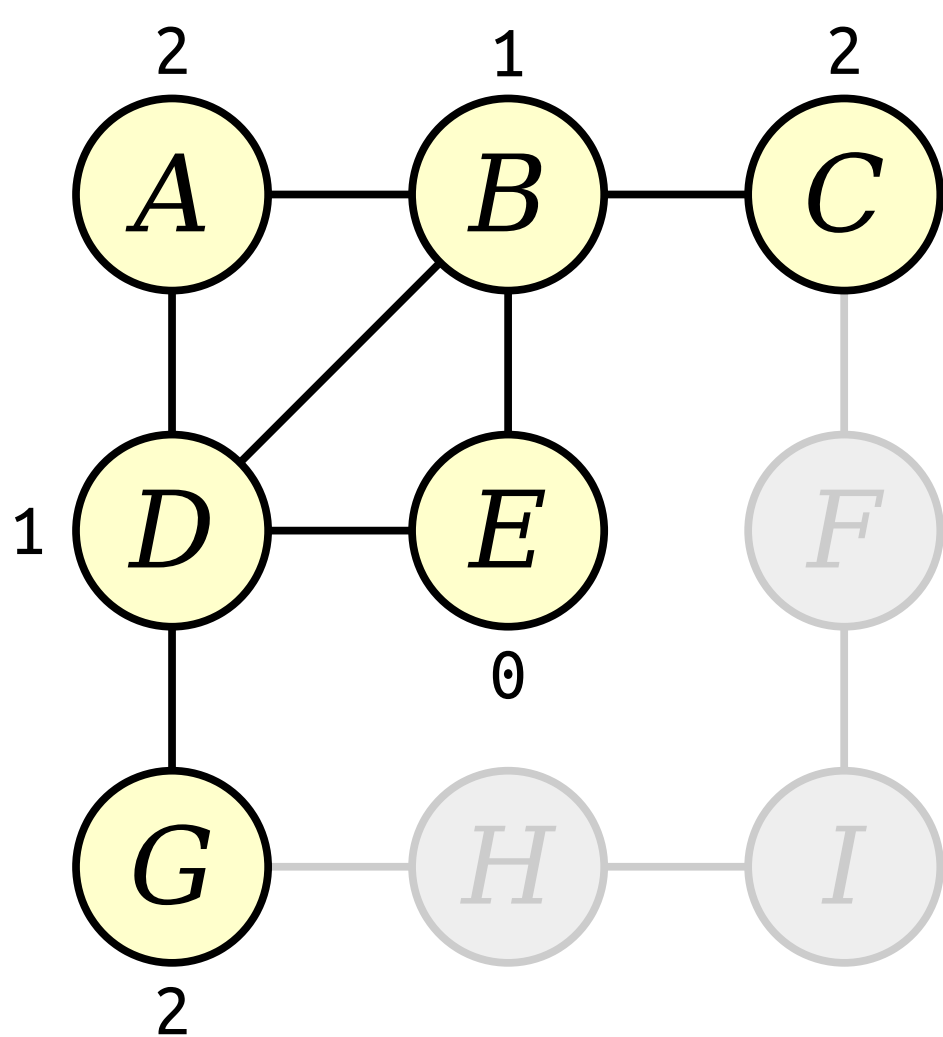


Visit nodes in ascending order of distance from the start node E .

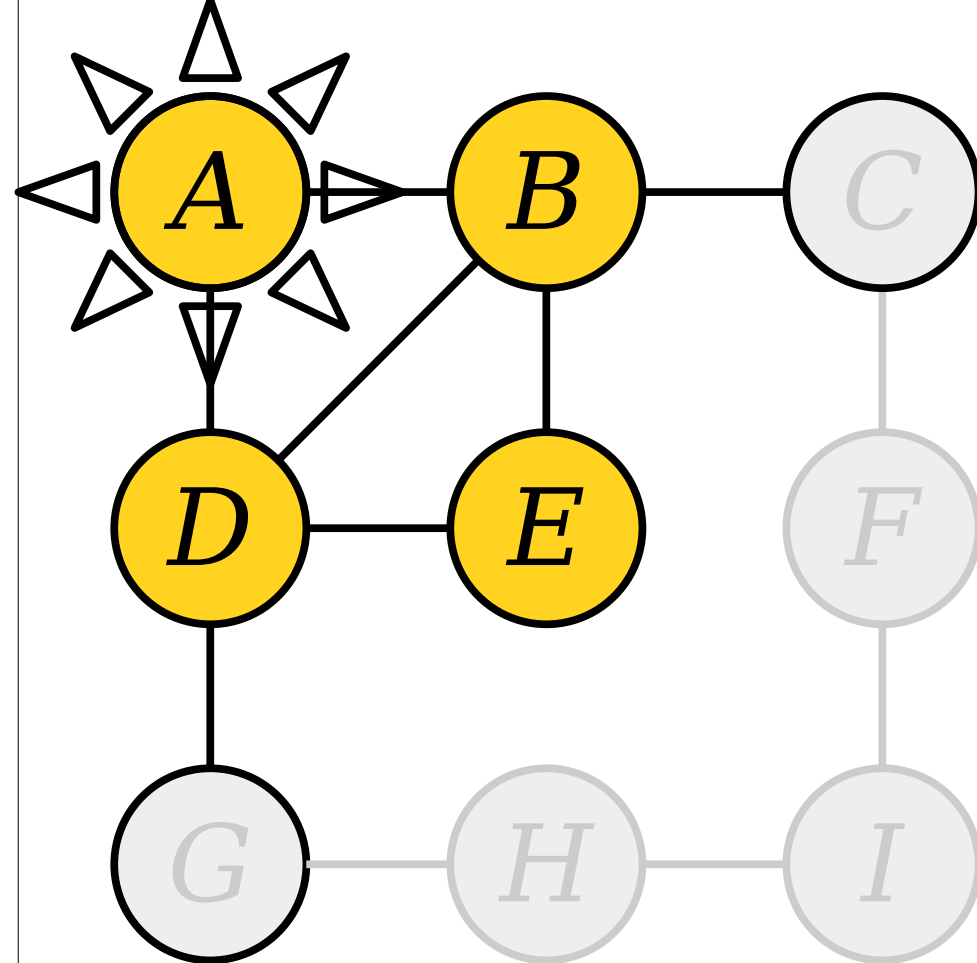


Queue: G C

Load newly-discovered nodes into a queue.

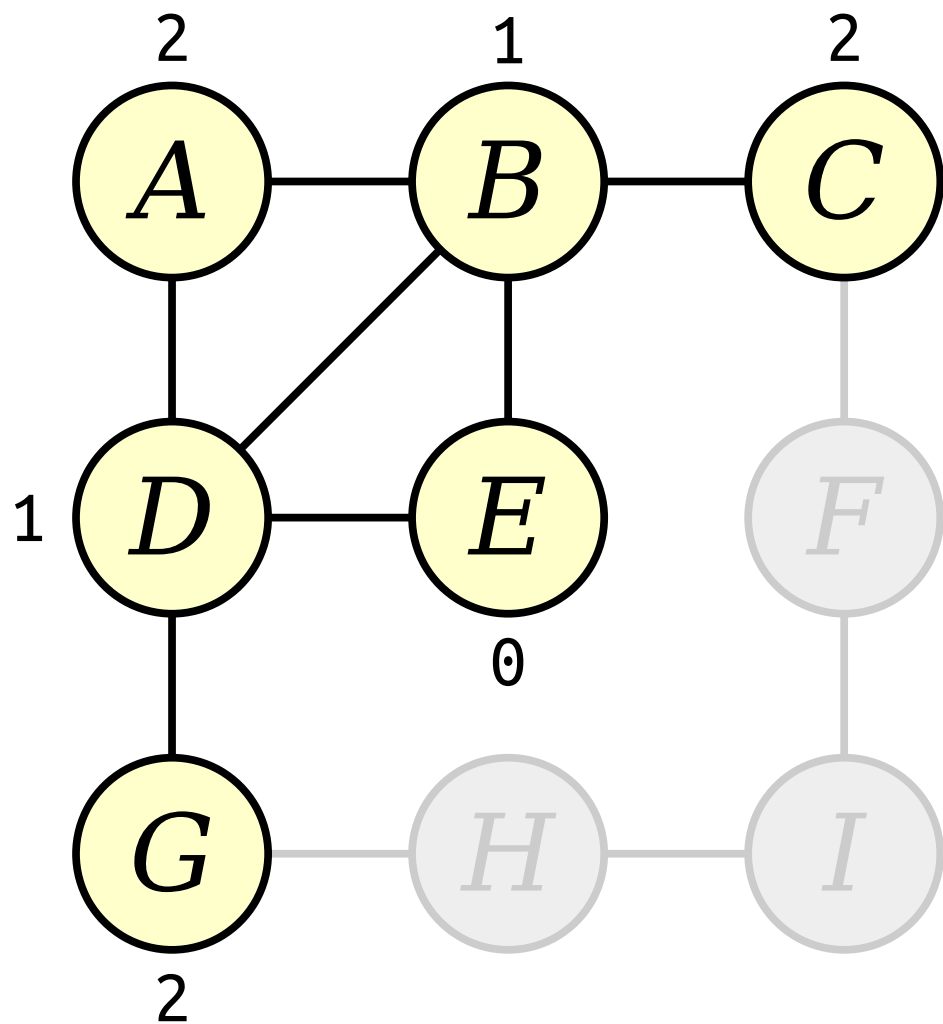


Visit nodes in ascending order of distance from the start node *E*.

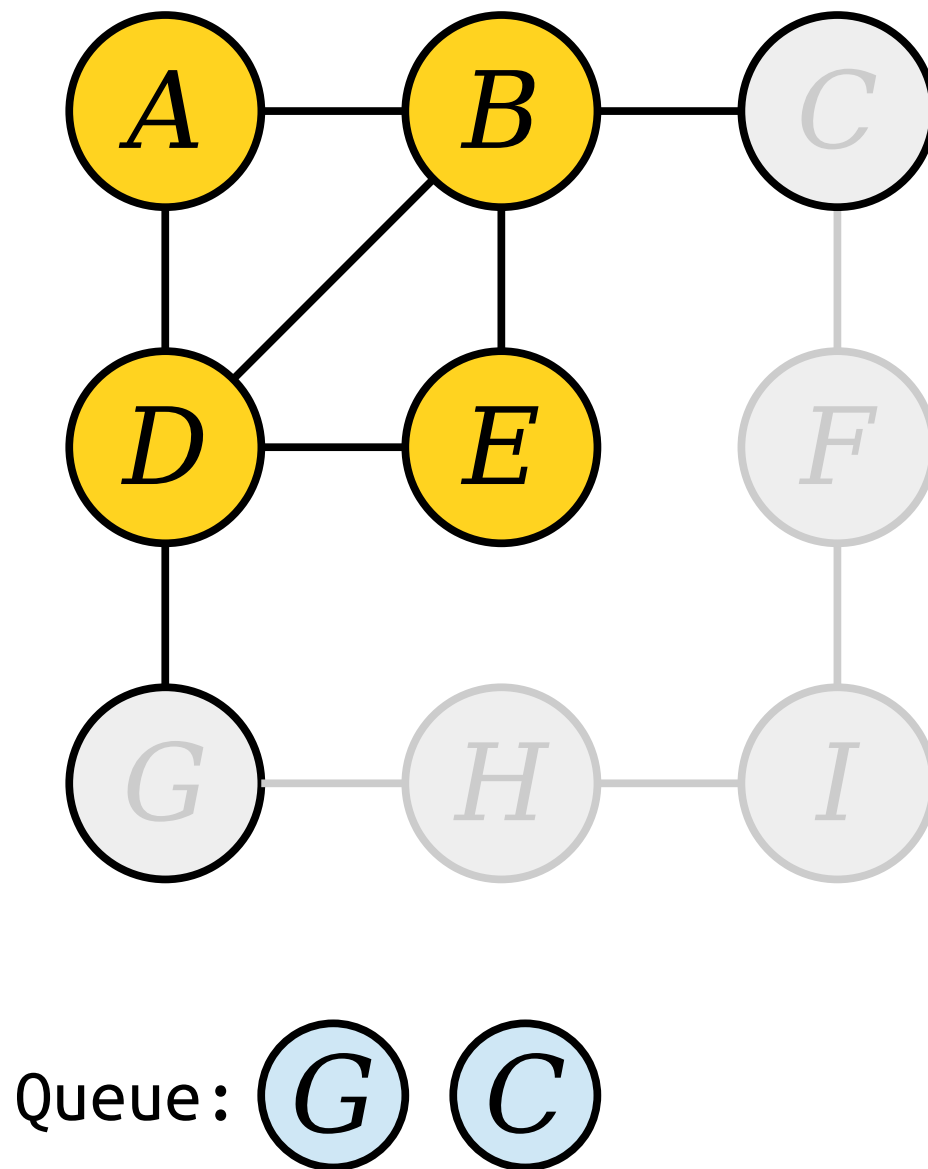


Queue: *G* *C*

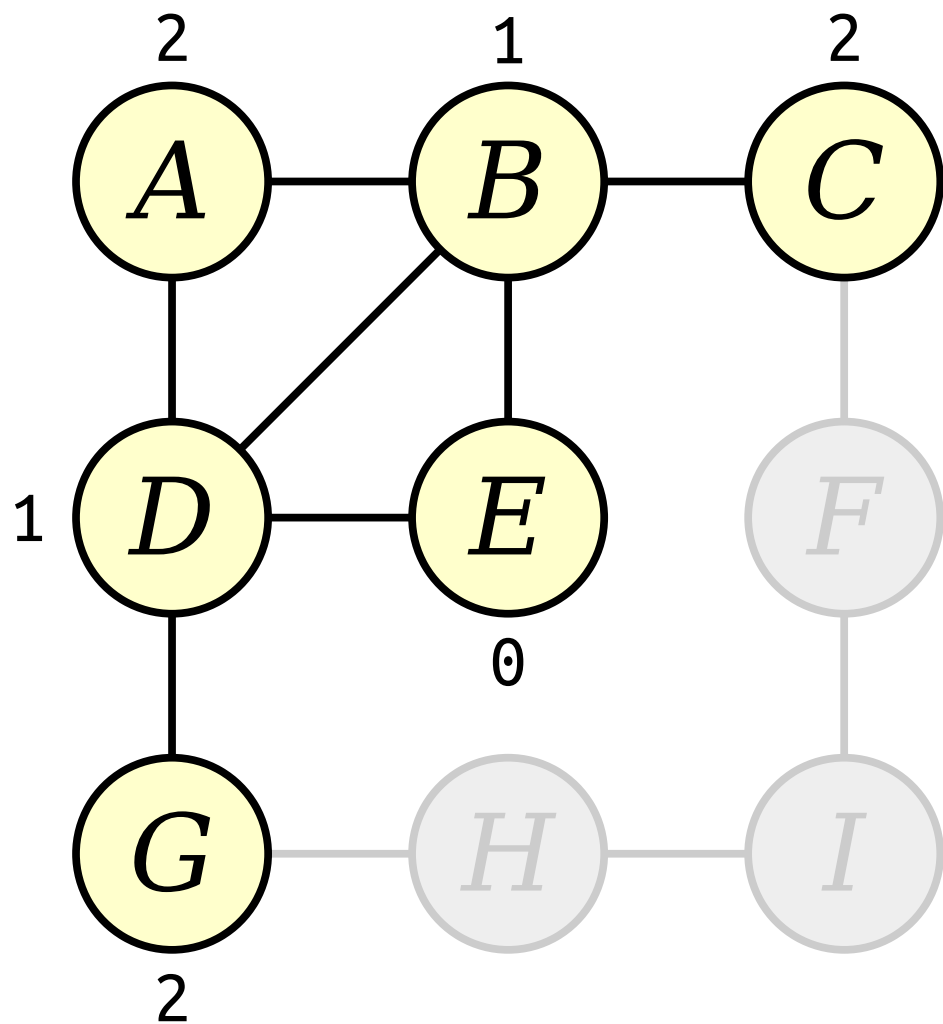
Load newly-discovered nodes into a queue.



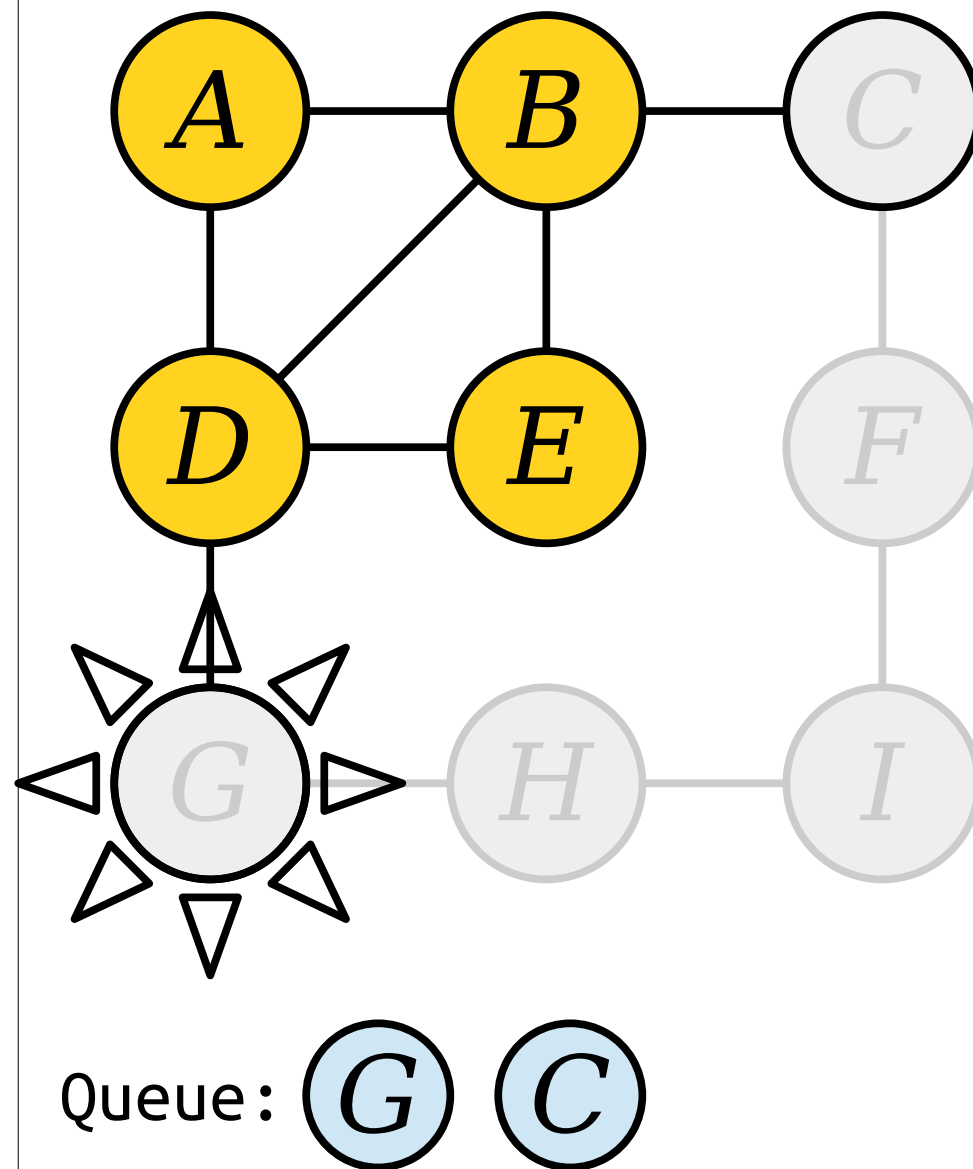
Visit nodes in ascending order of distance from the start node E .



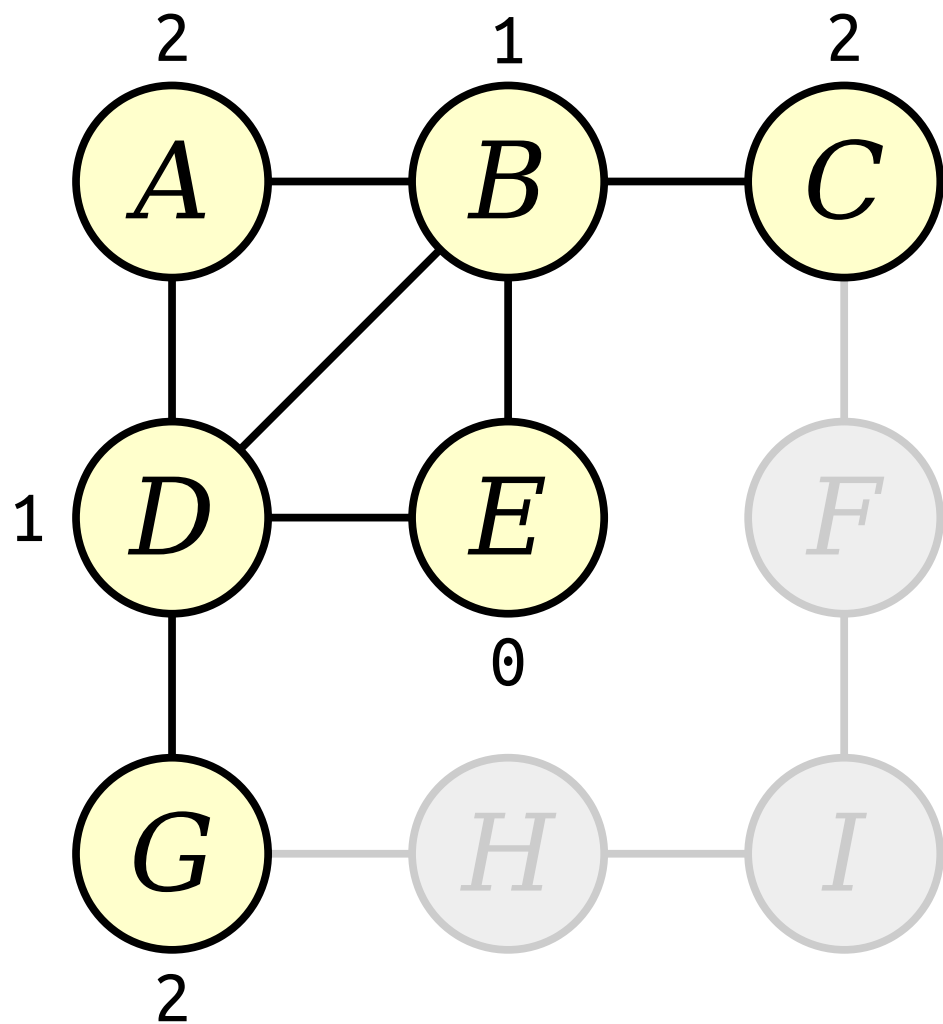
Load newly-discovered nodes into a queue.



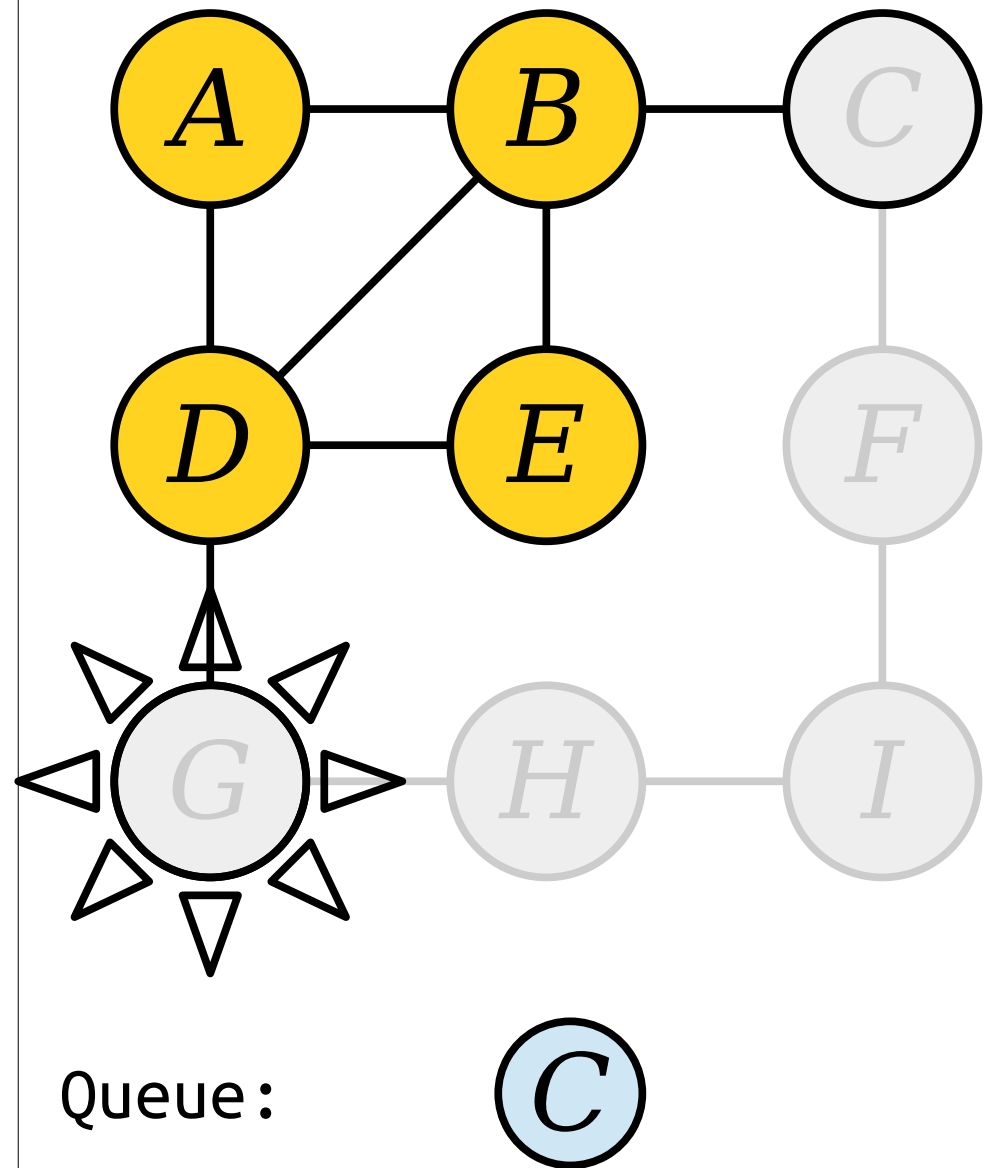
Visit nodes in ascending order of distance from the start node *E*.



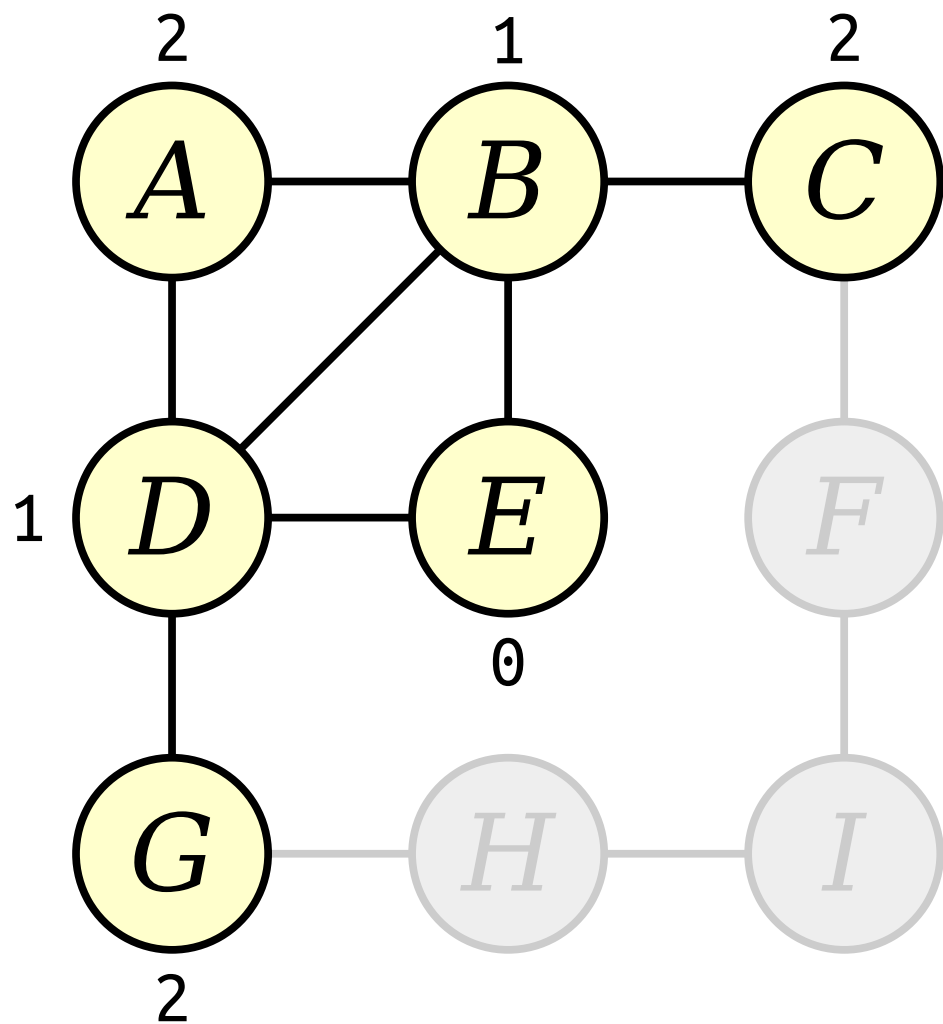
Load newly-discovered nodes into a queue.



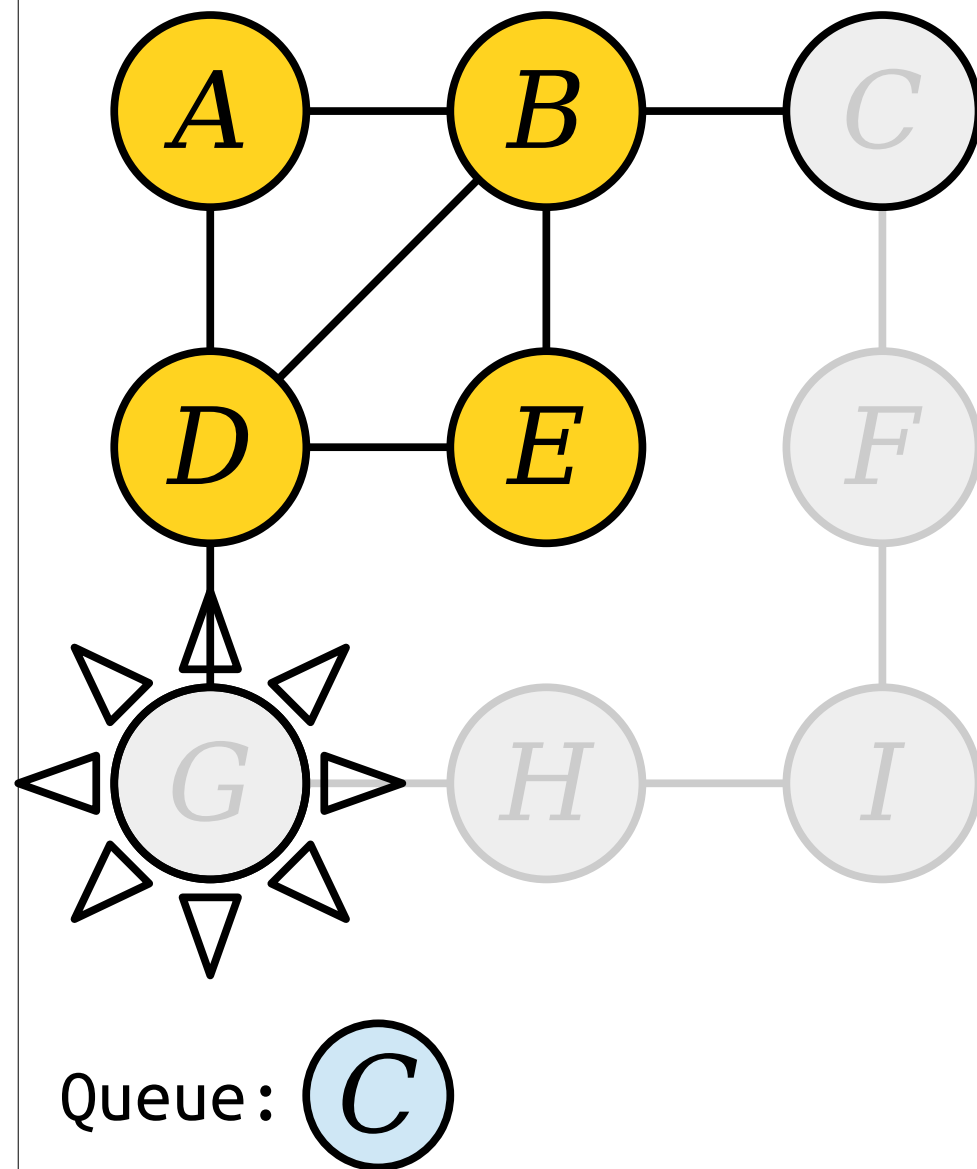
Visit nodes in ascending order of distance from the start node *E*.



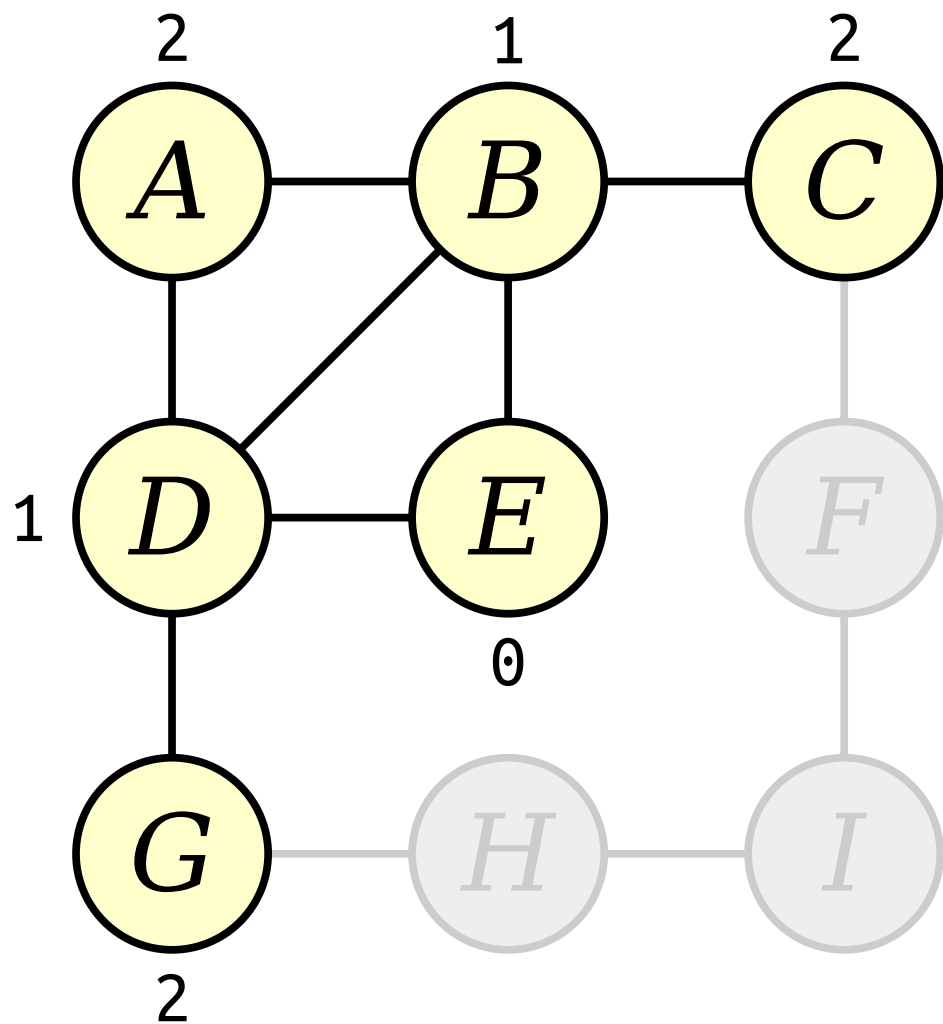
Load newly-discovered nodes into a queue.



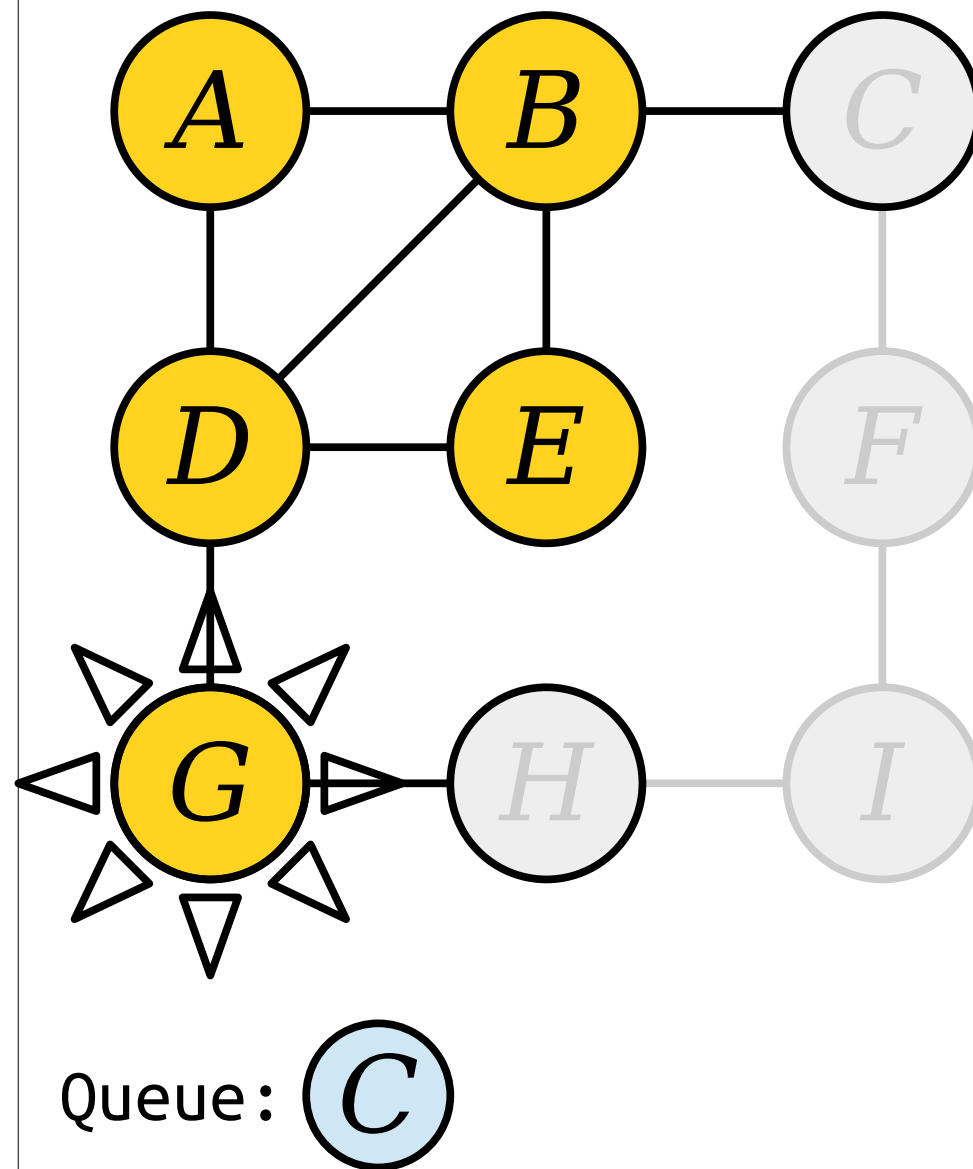
Visit nodes in ascending order of distance from the start node *E*.



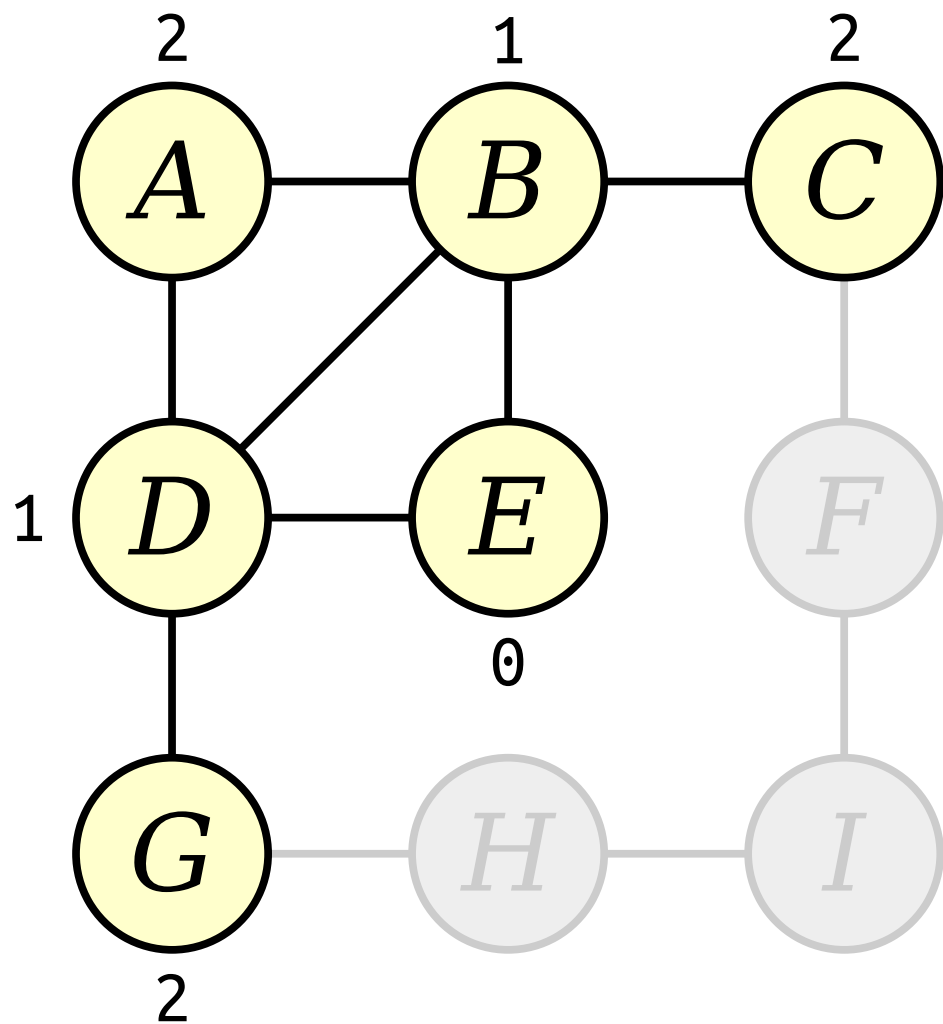
Load newly-discovered nodes into a queue.



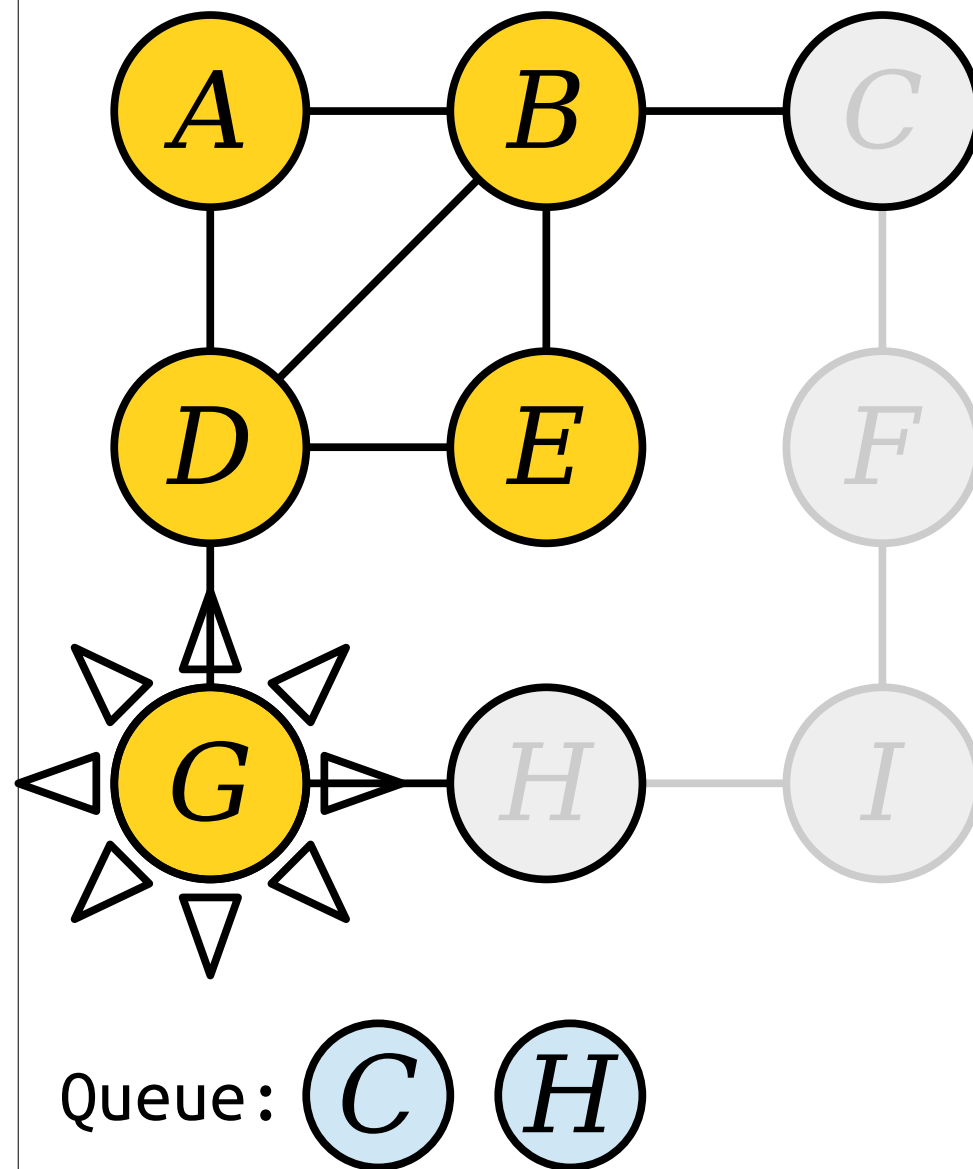
Visit nodes in ascending order of distance from the start node *E*.



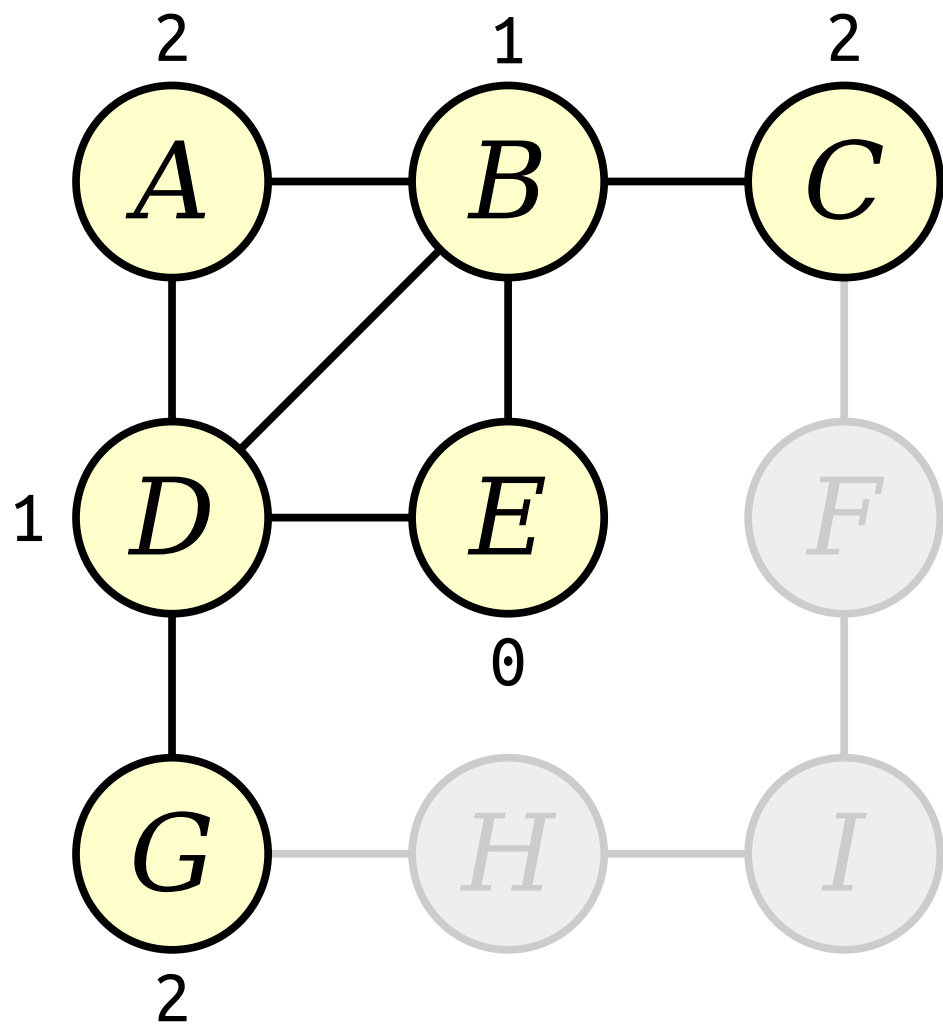
Load newly-discovered nodes into a queue.



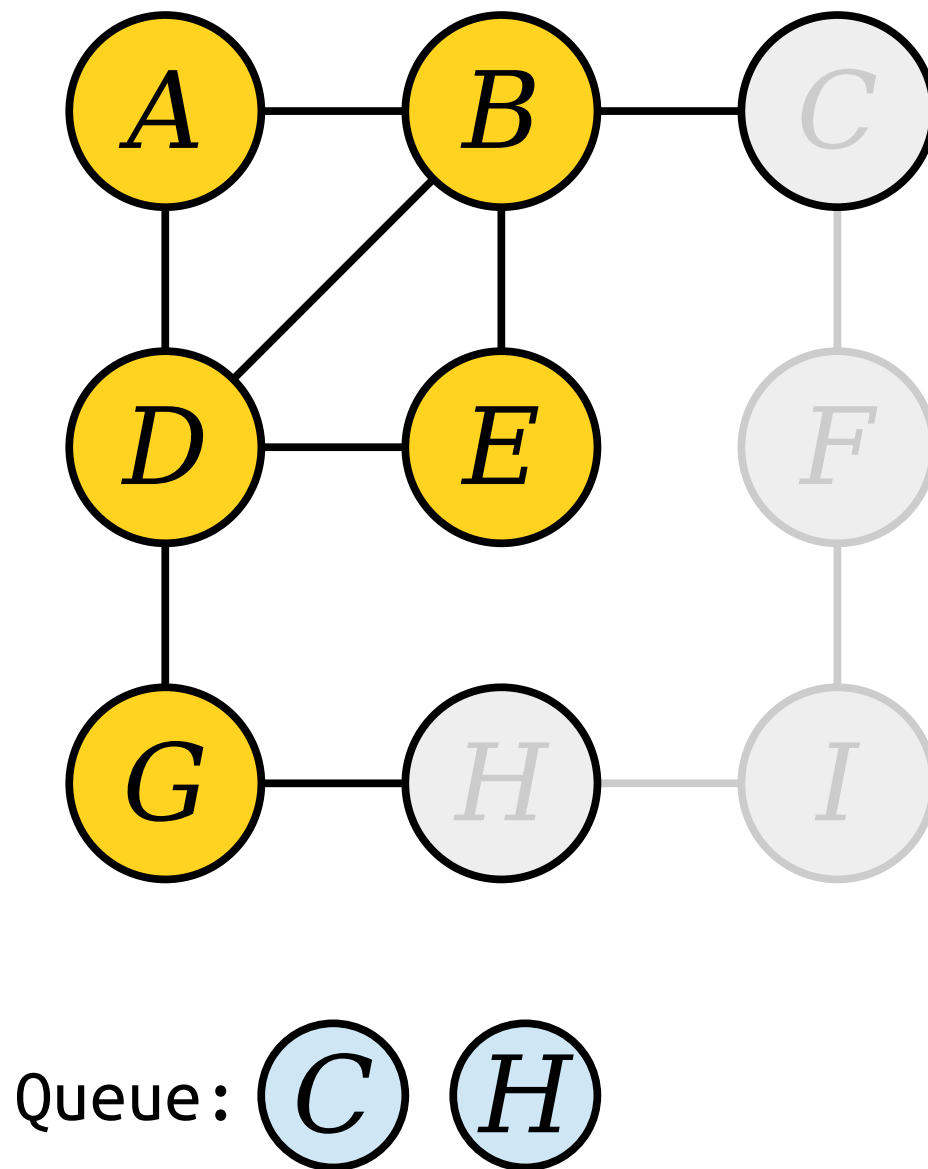
Visit nodes in ascending order of distance from the start node *E*.



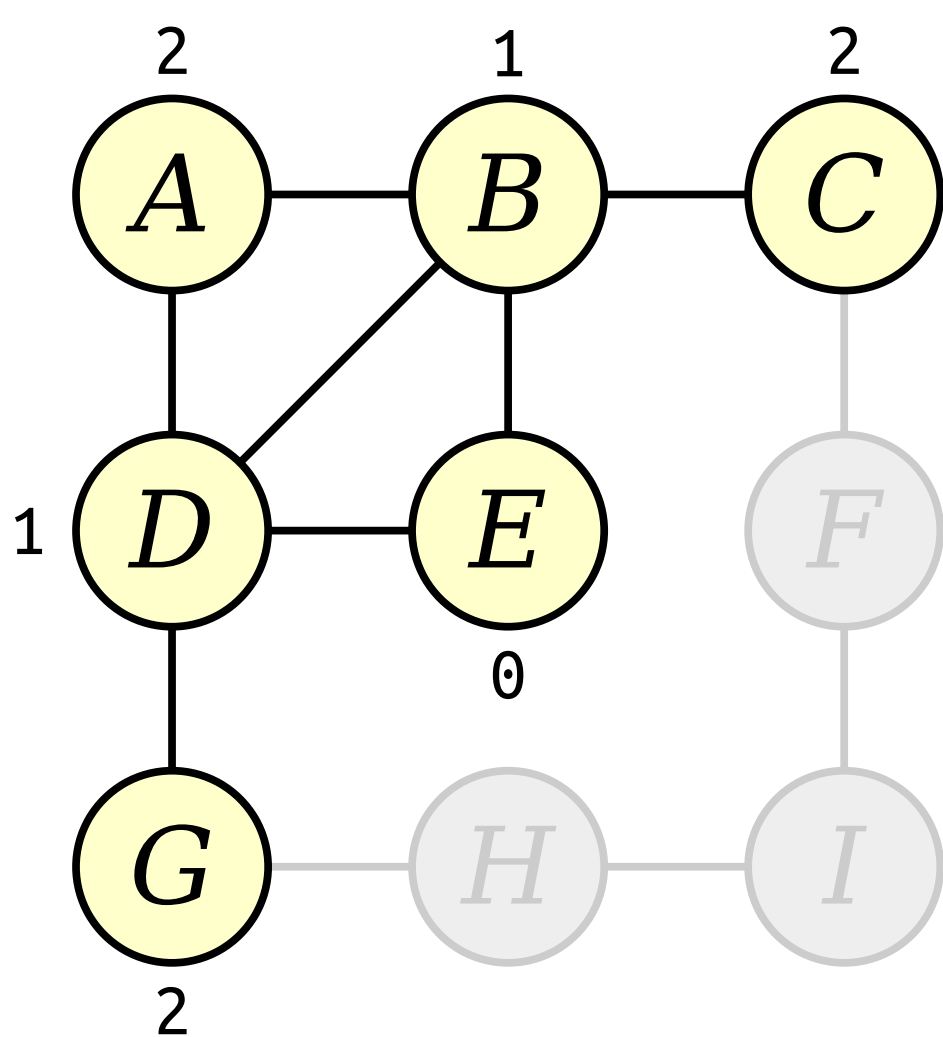
Load newly-discovered nodes into a queue.



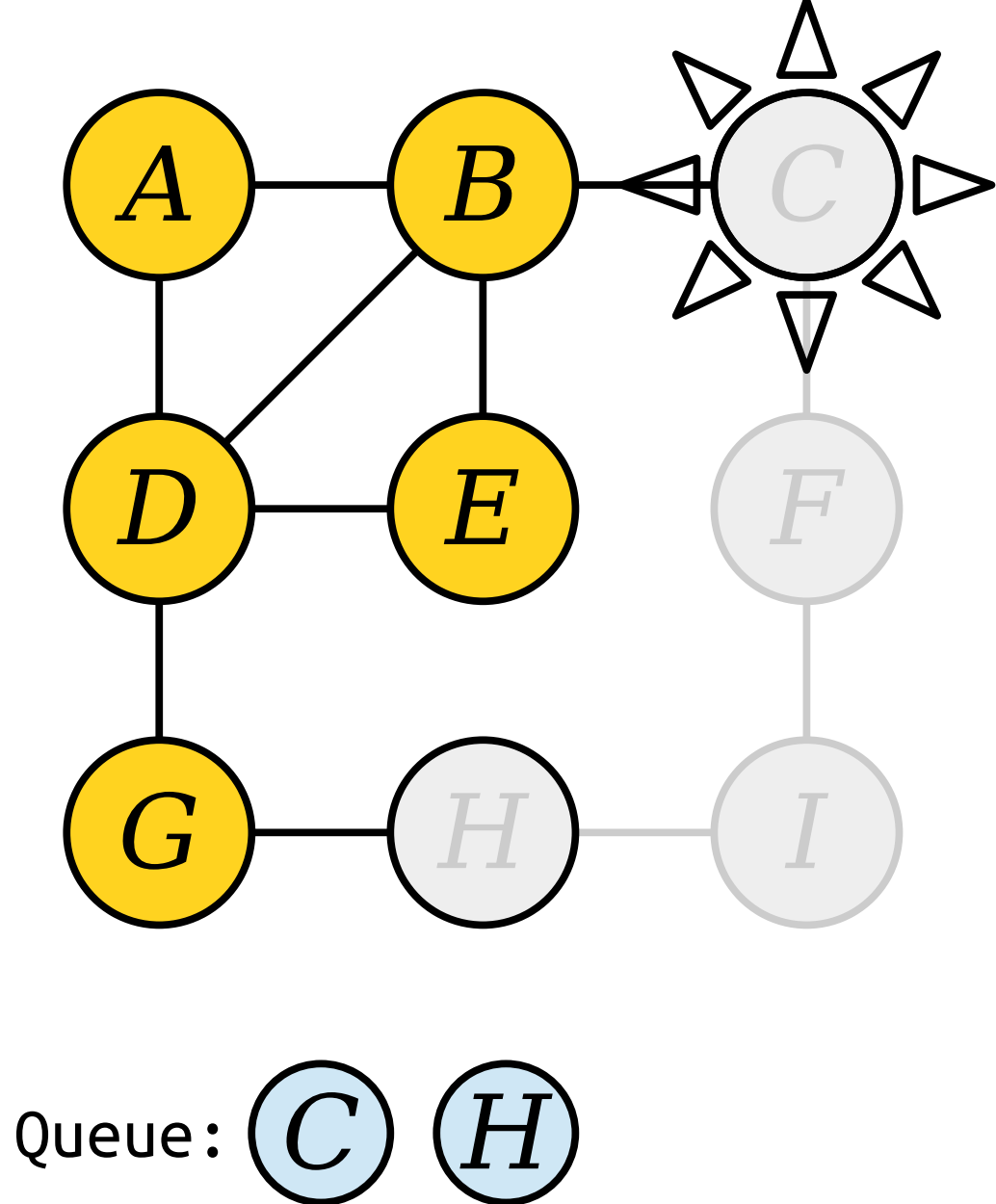
Visit nodes in ascending order of distance from the start node E .



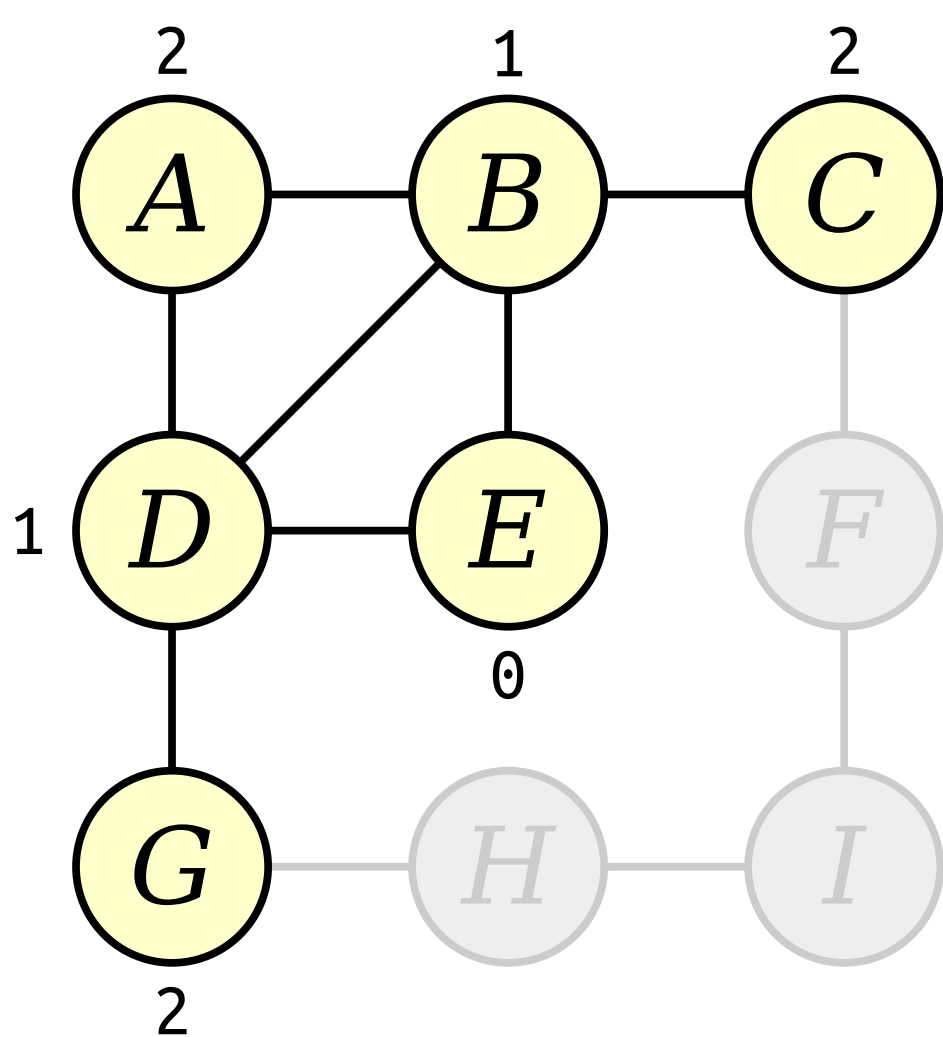
Load newly-discovered nodes into a queue.



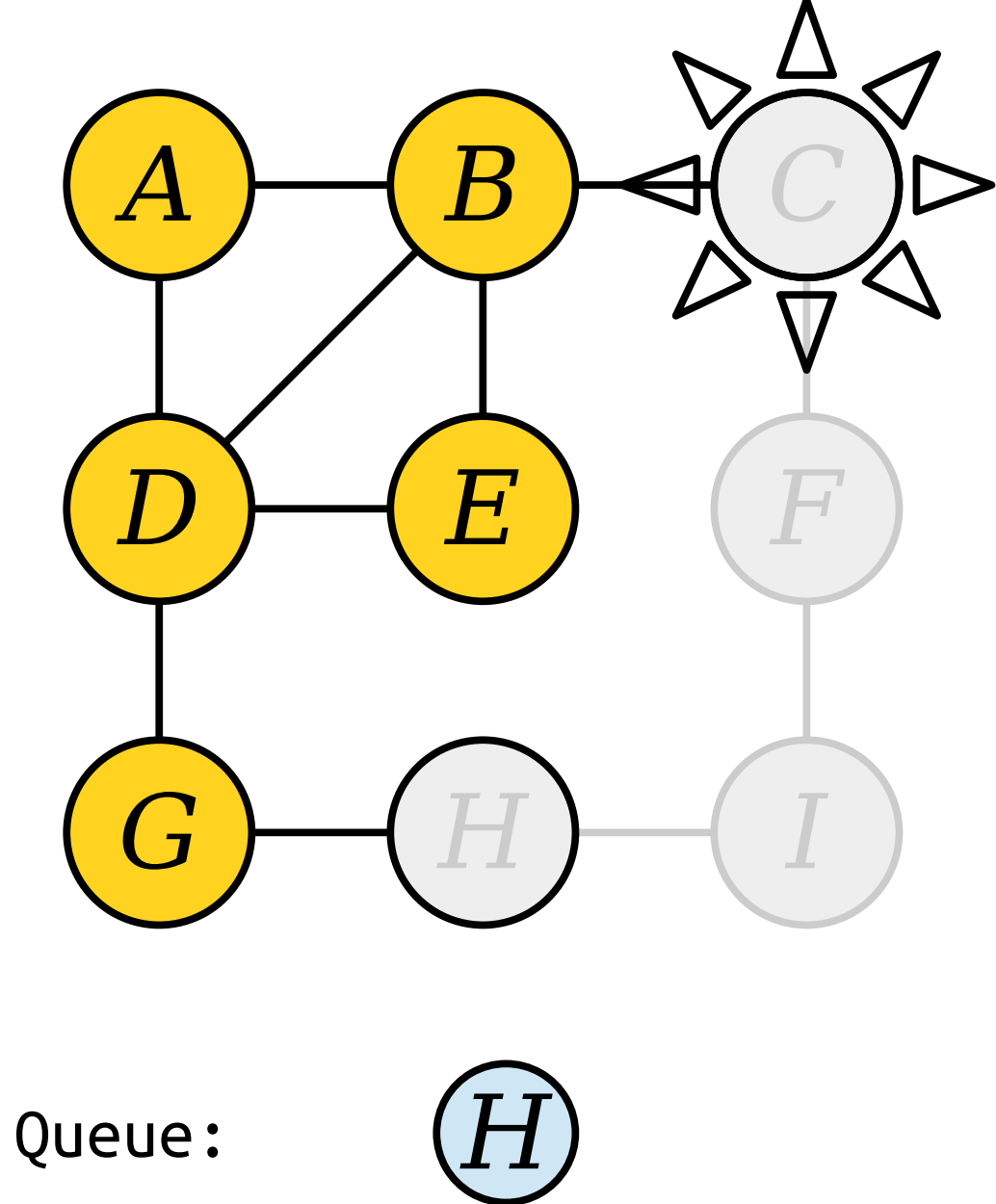
Visit nodes in ascending order of distance from the start node E .



Load newly-discovered nodes into a queue.



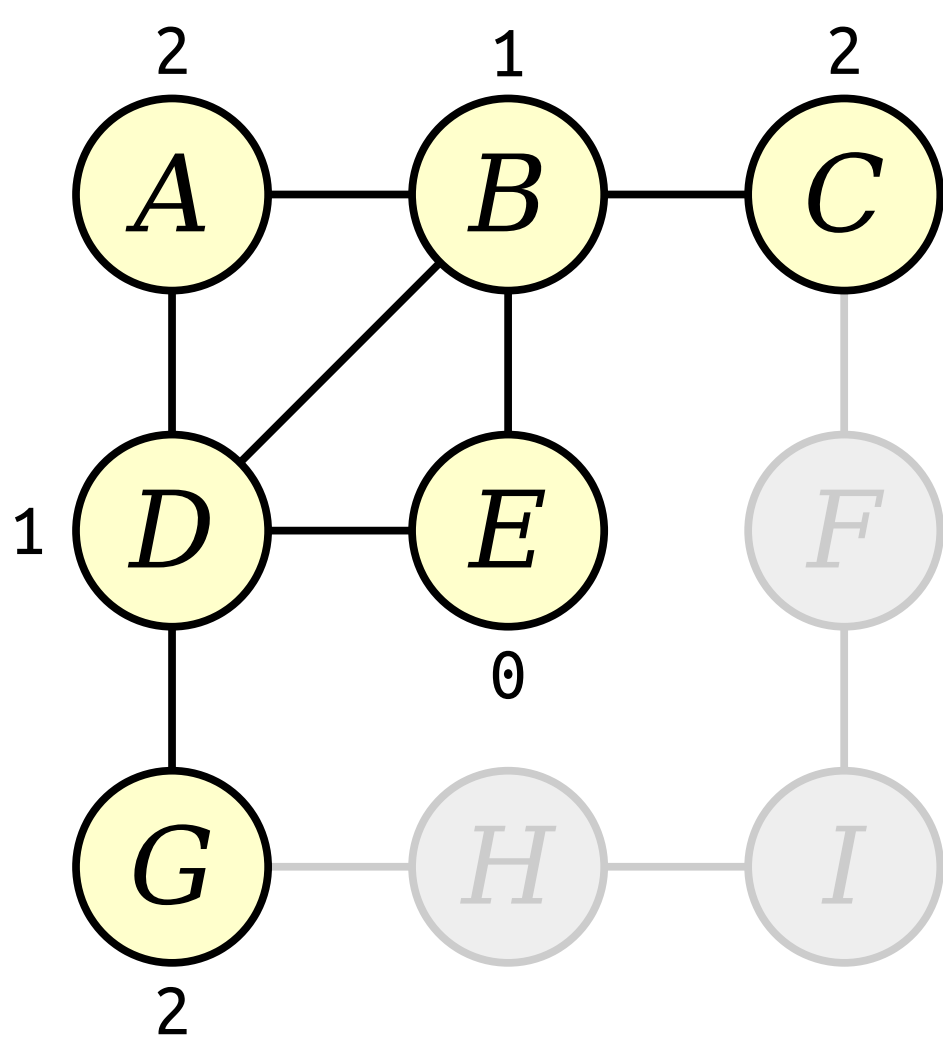
Visit nodes in ascending order of distance from the start node *E*.



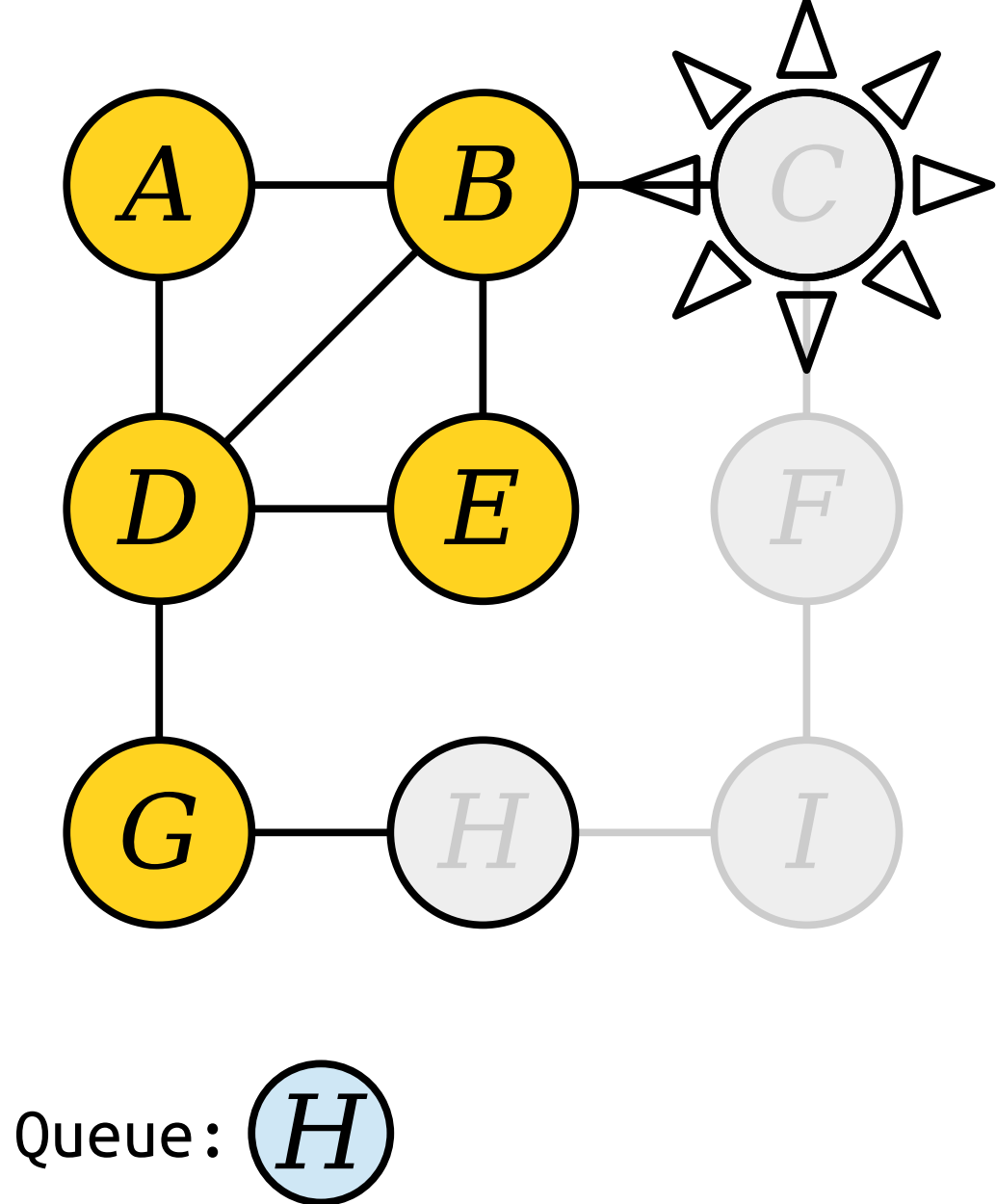
Queue:



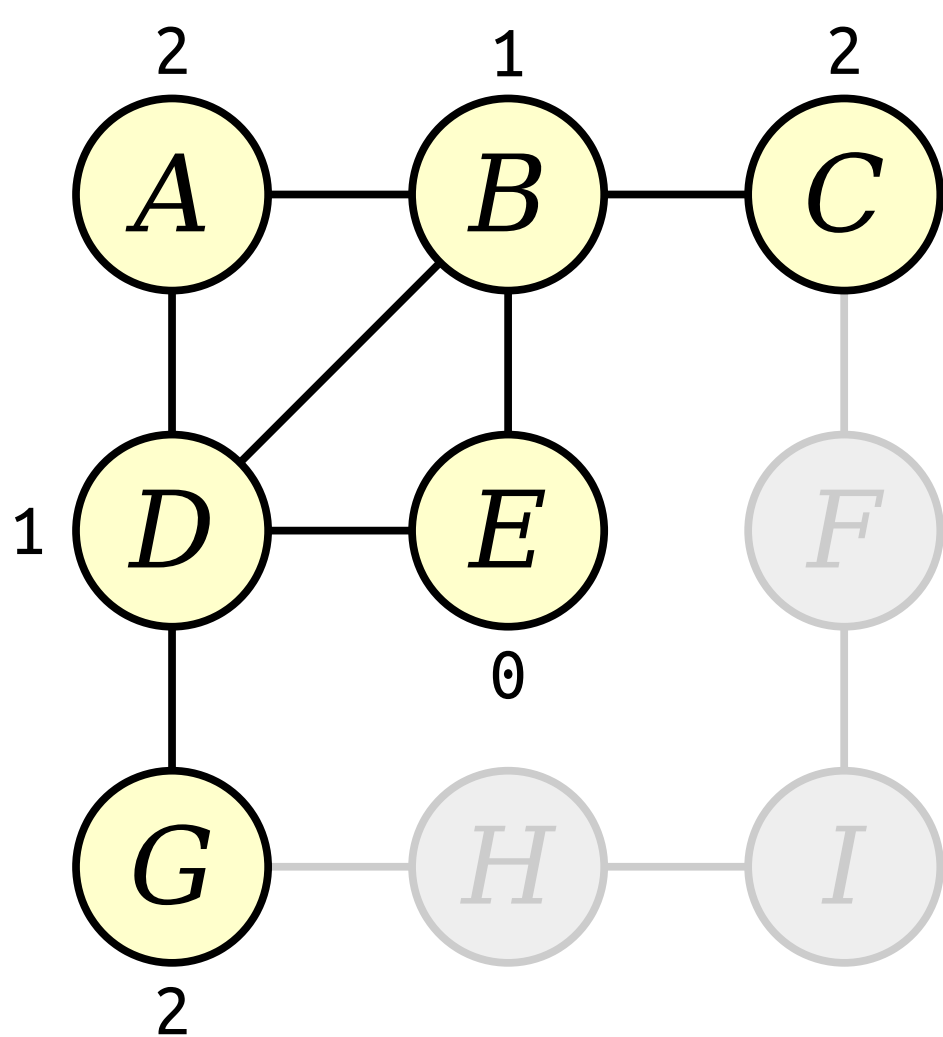
Load newly-discovered nodes into a queue.



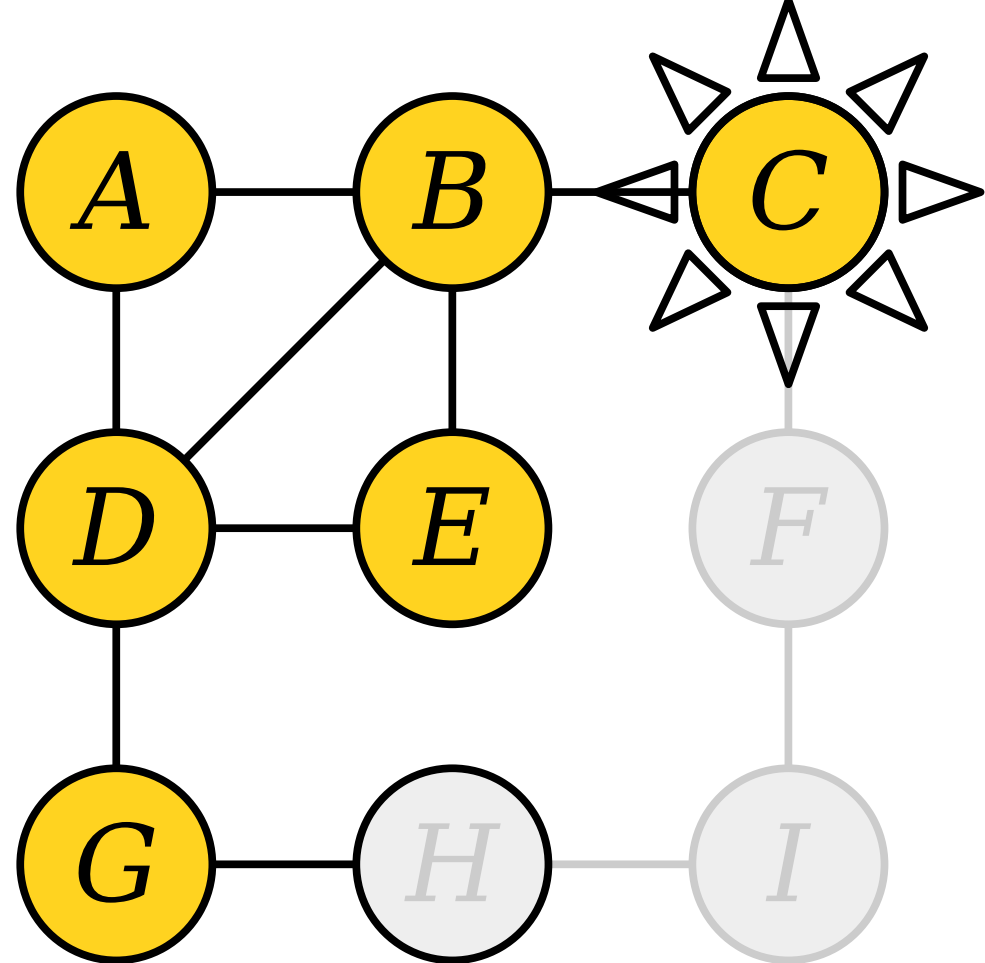
Visit nodes in ascending order of distance from the start node *E*.



Load newly-discovered nodes into a queue.

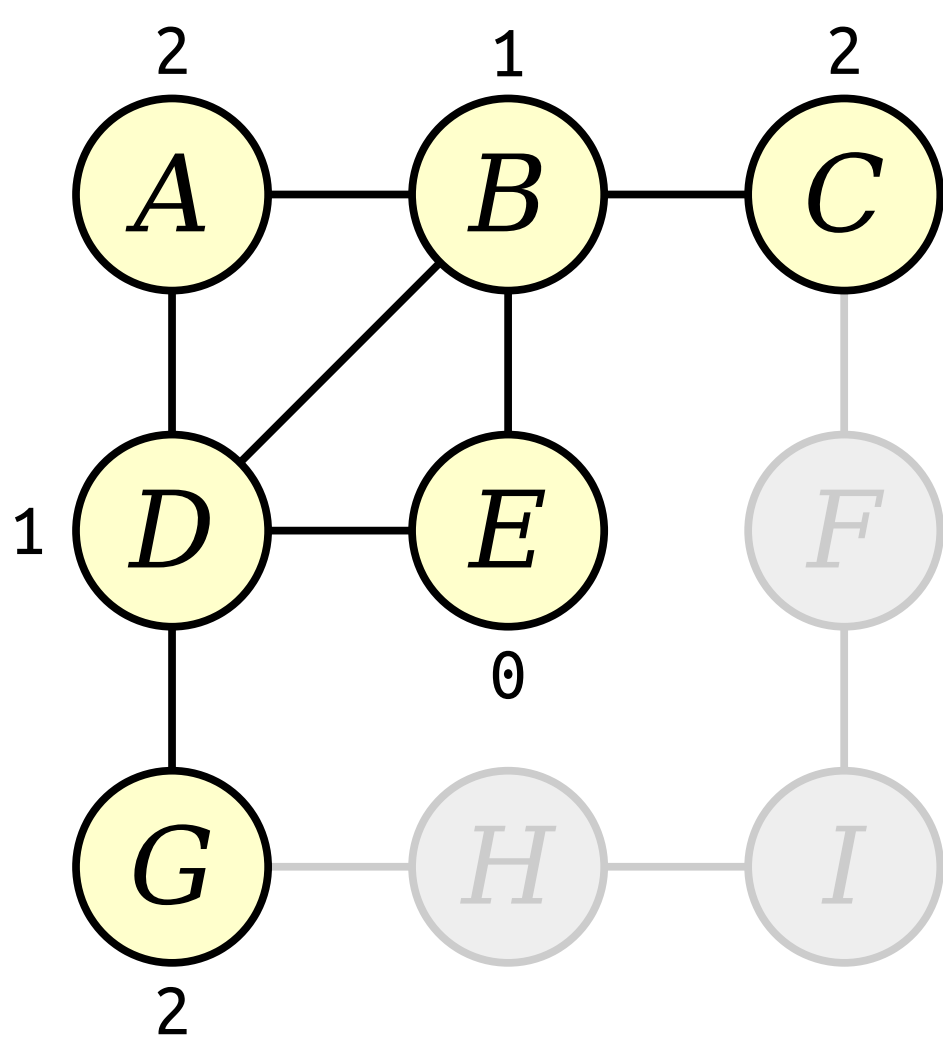


Visit nodes in ascending order of distance from the start node E .

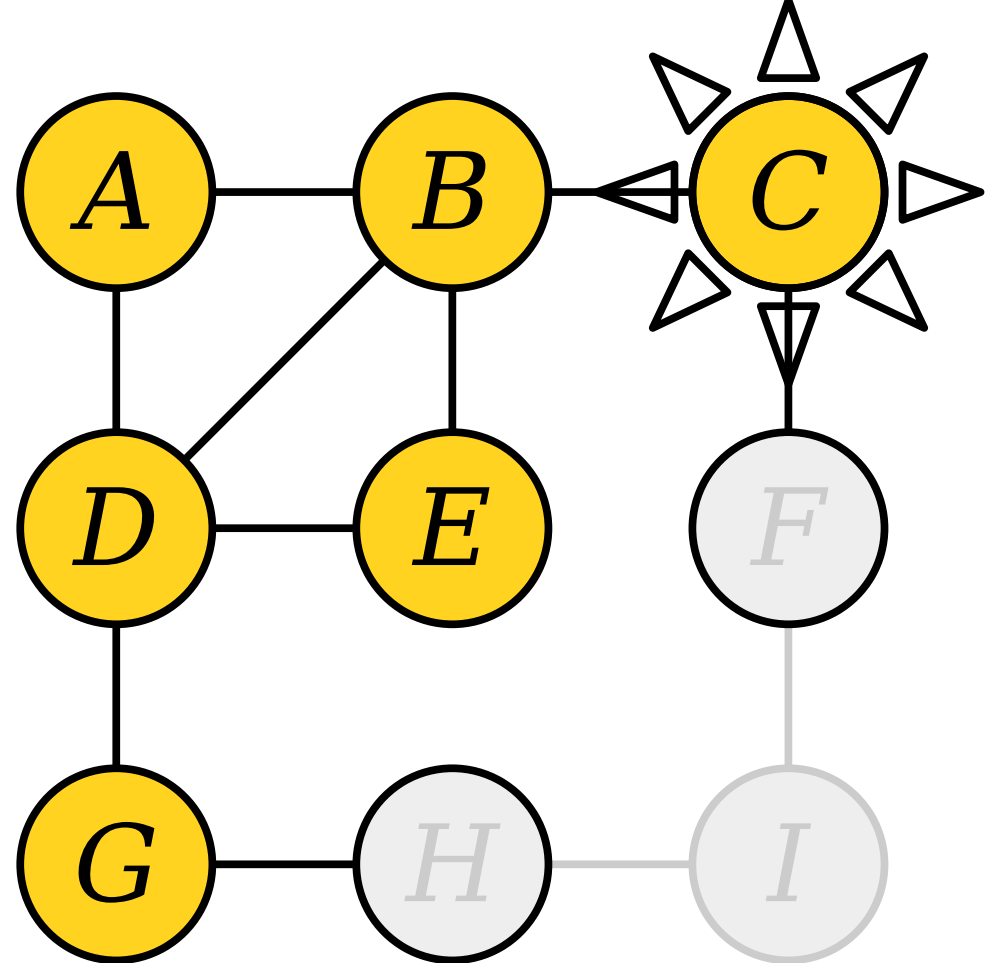


Queue: H

Load newly-discovered nodes into a queue.

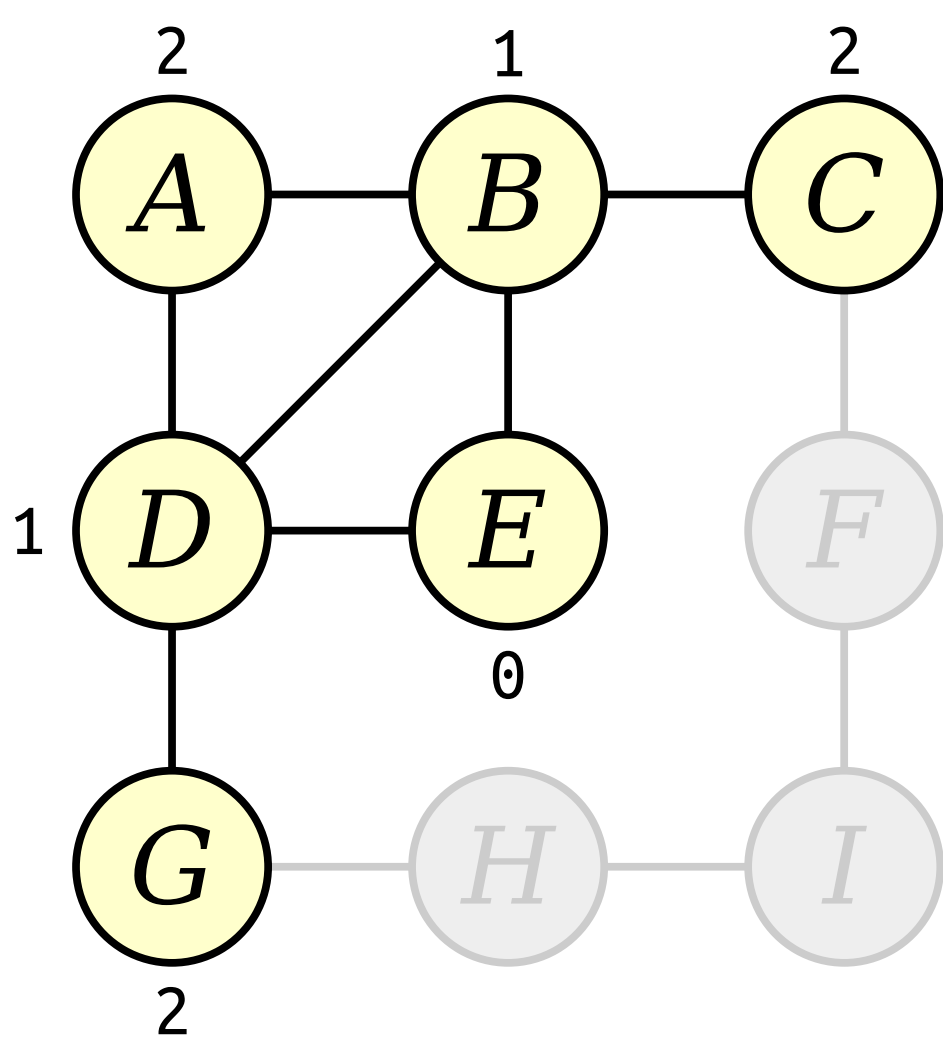


Visit nodes in ascending order of distance from the start node *E*.

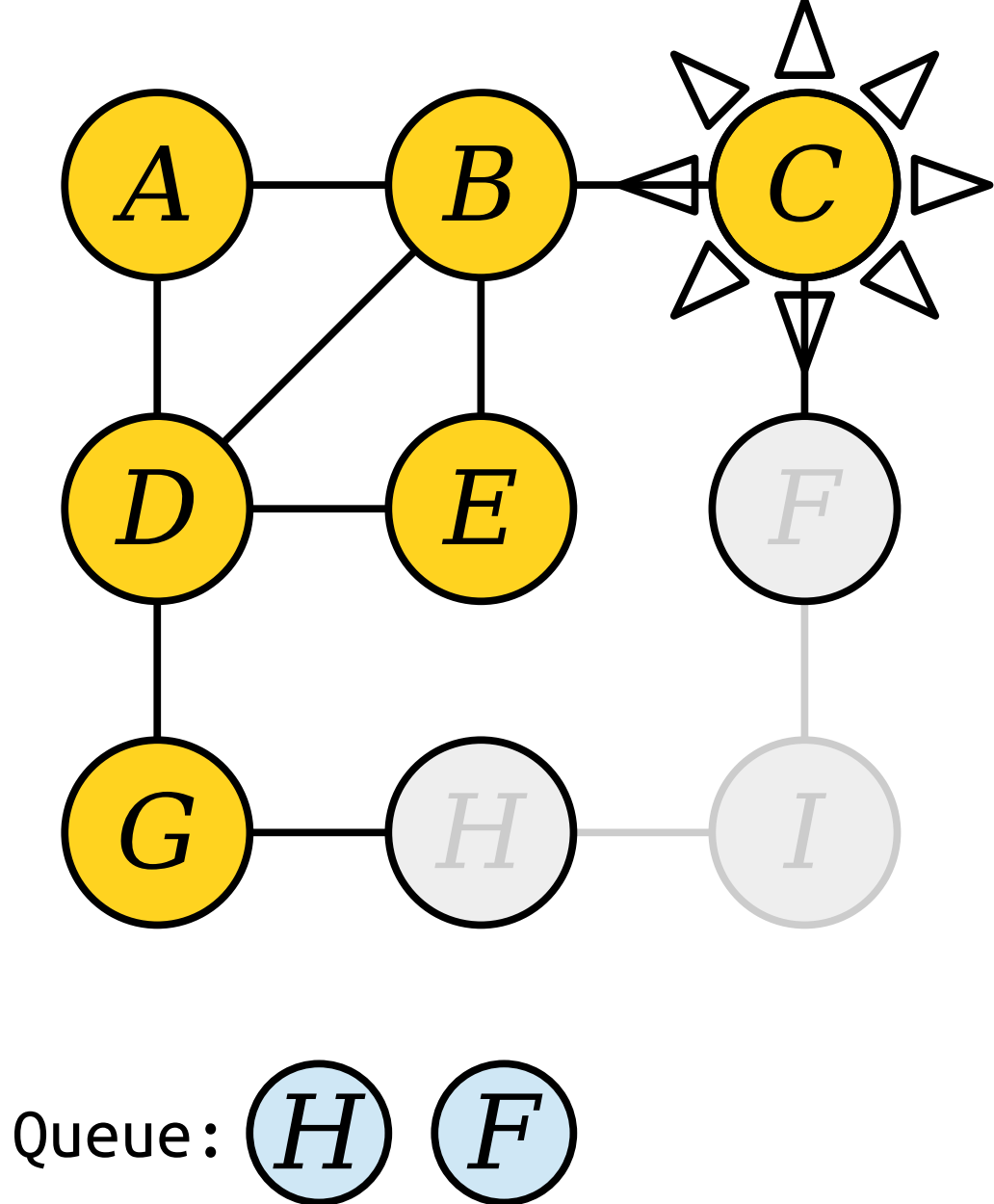


Queue: *H*

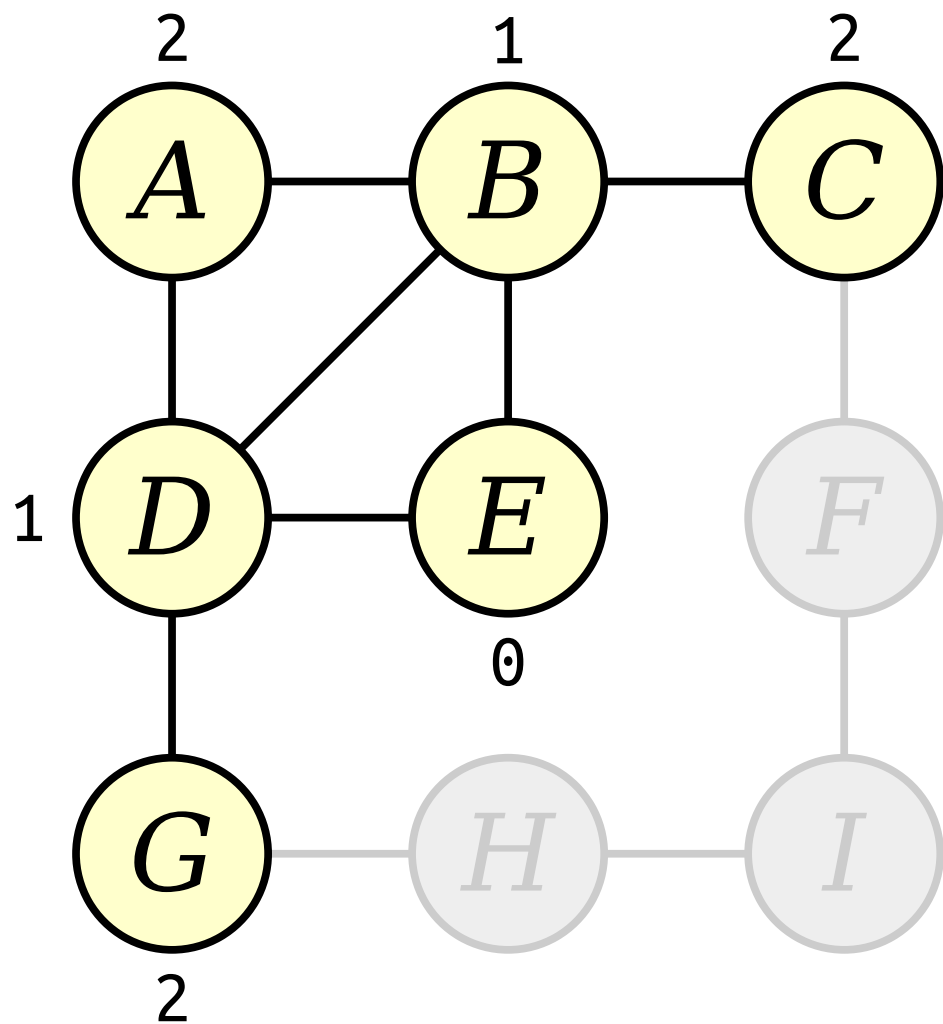
Load newly-discovered nodes into a queue.



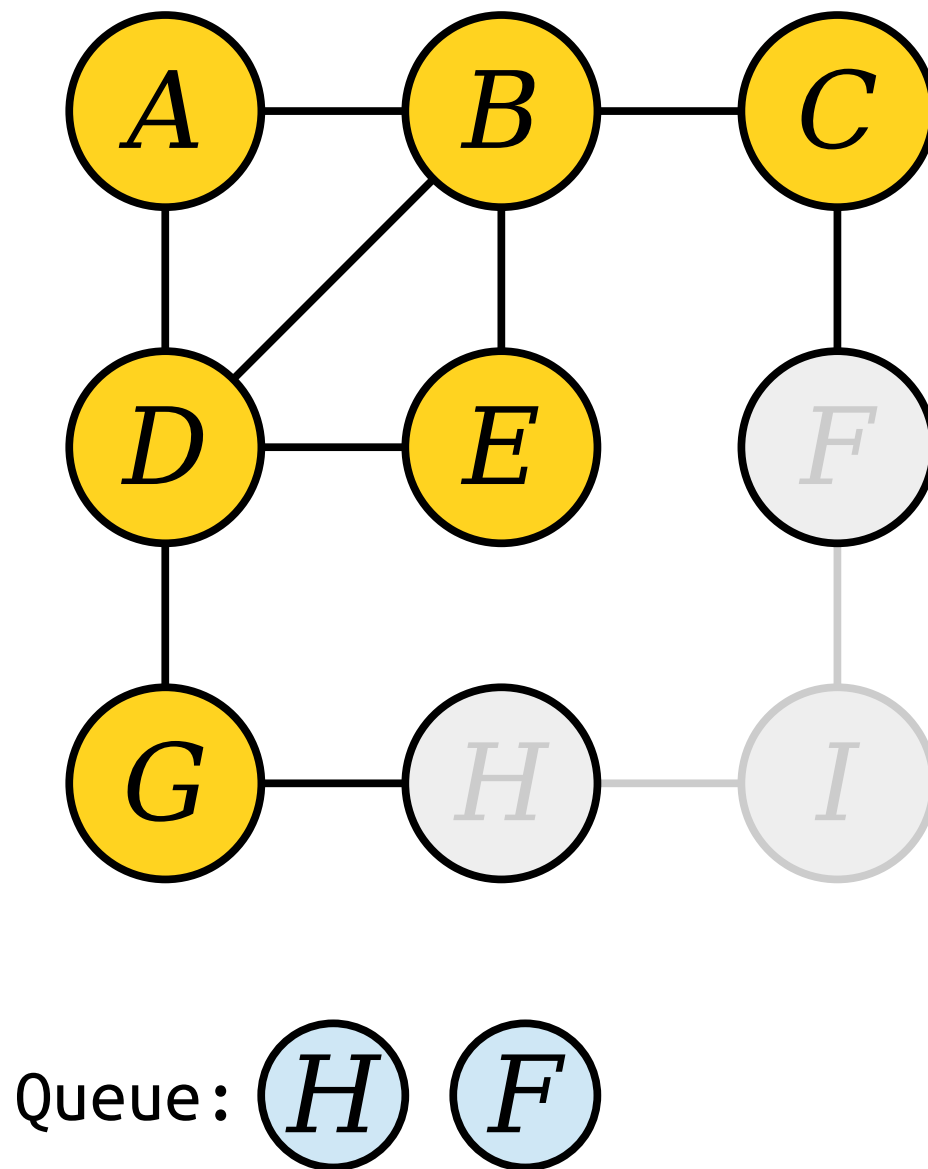
Visit nodes in ascending order of distance from the start node E .



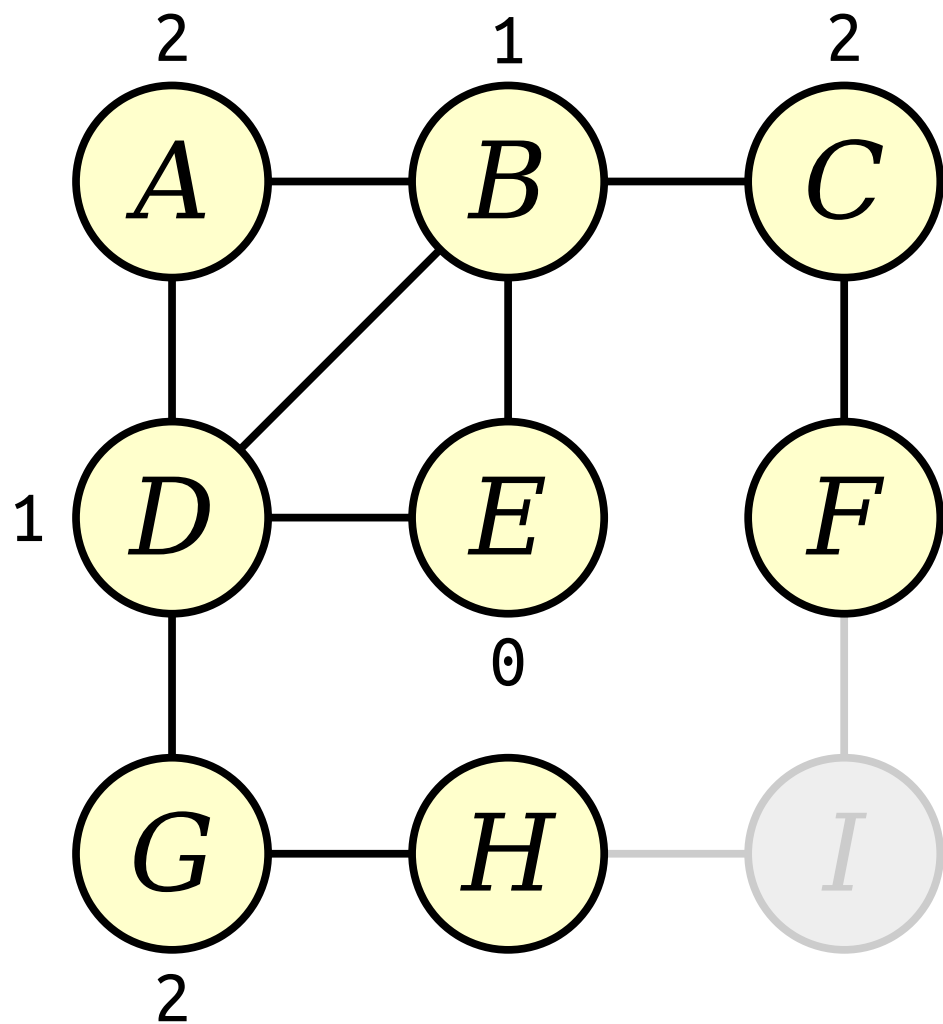
Load newly-discovered nodes into a queue.



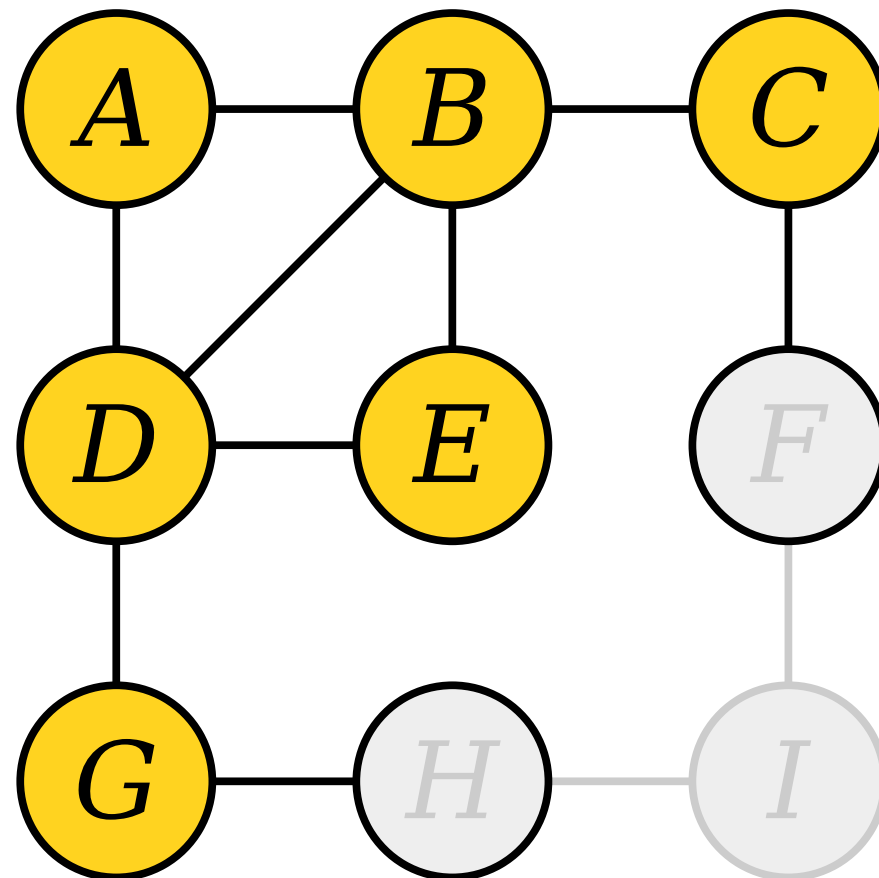
Visit nodes in ascending order of distance from the start node E .



Load newly-discovered nodes into a queue.

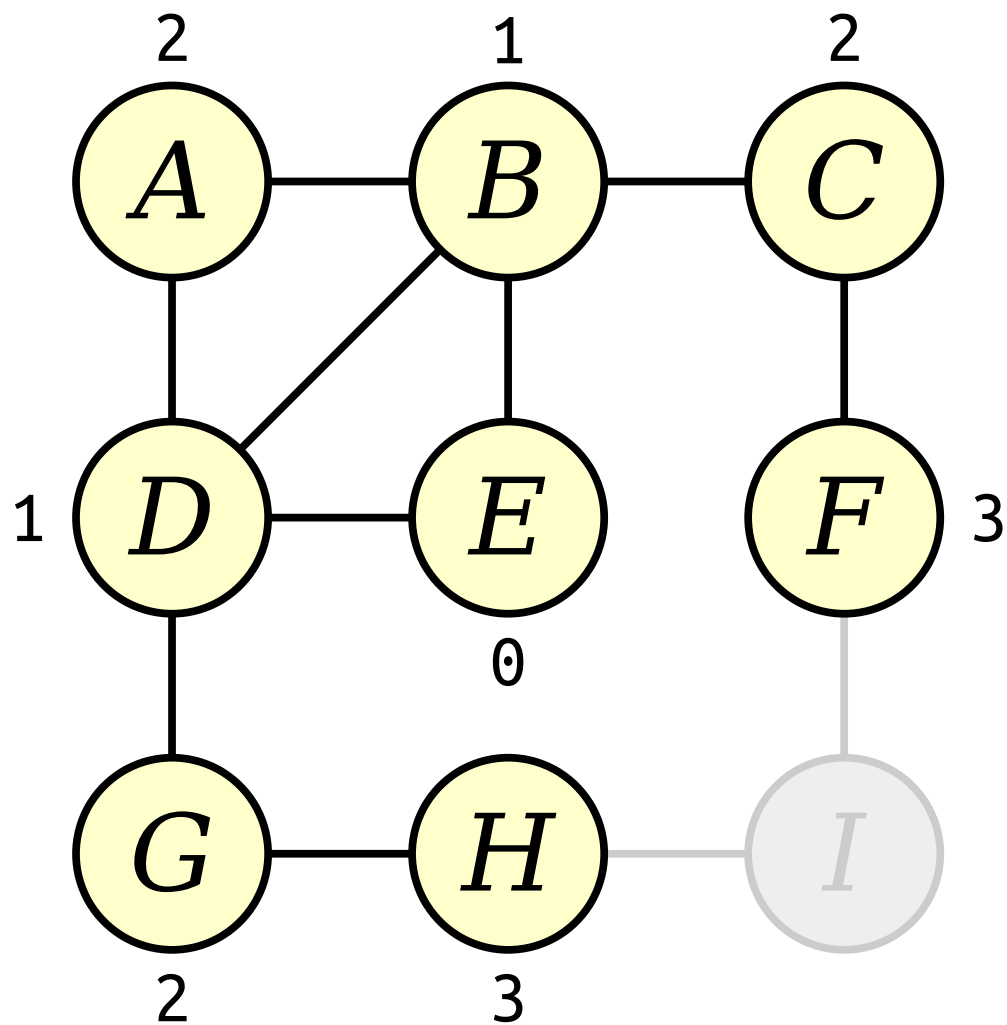


Visit nodes in ascending order of distance from the start node *E*.

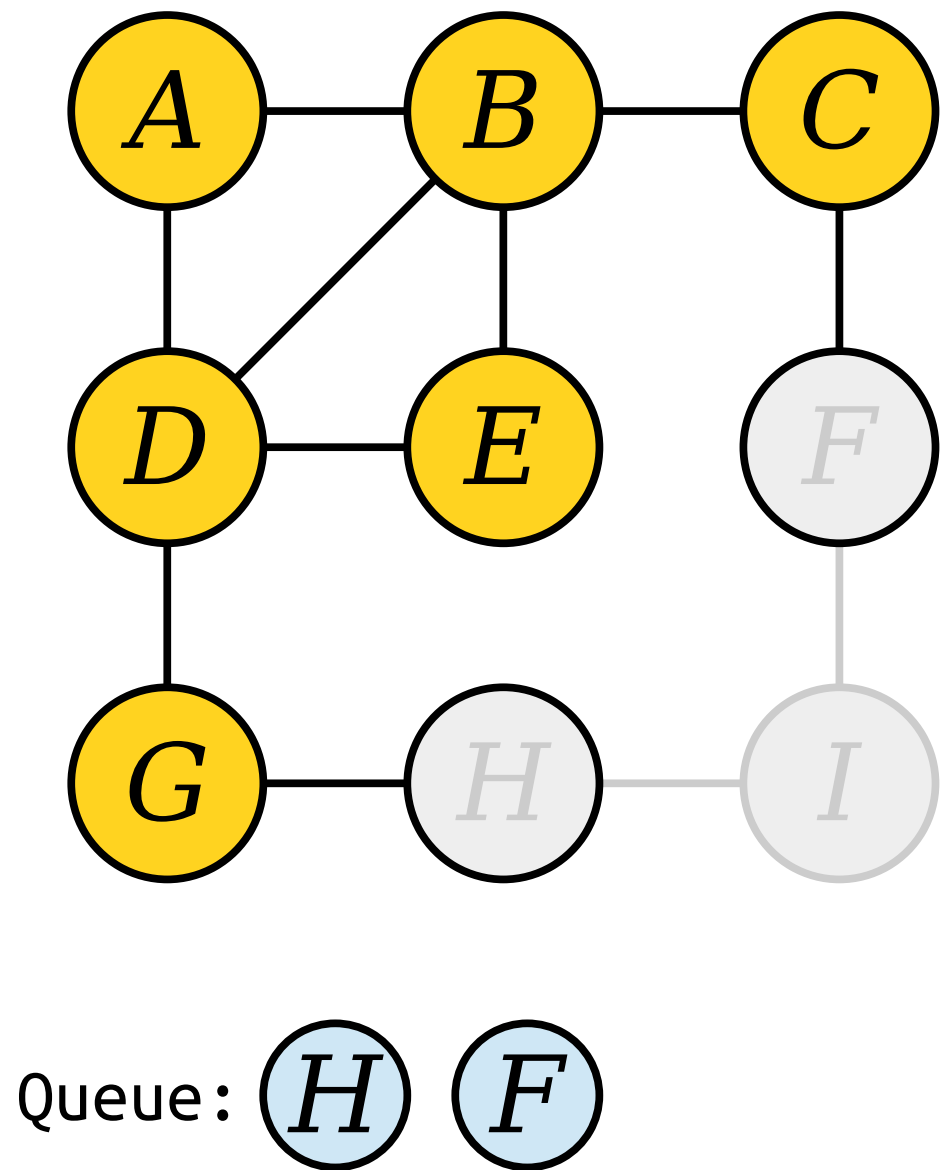


Queue: *H* *F*

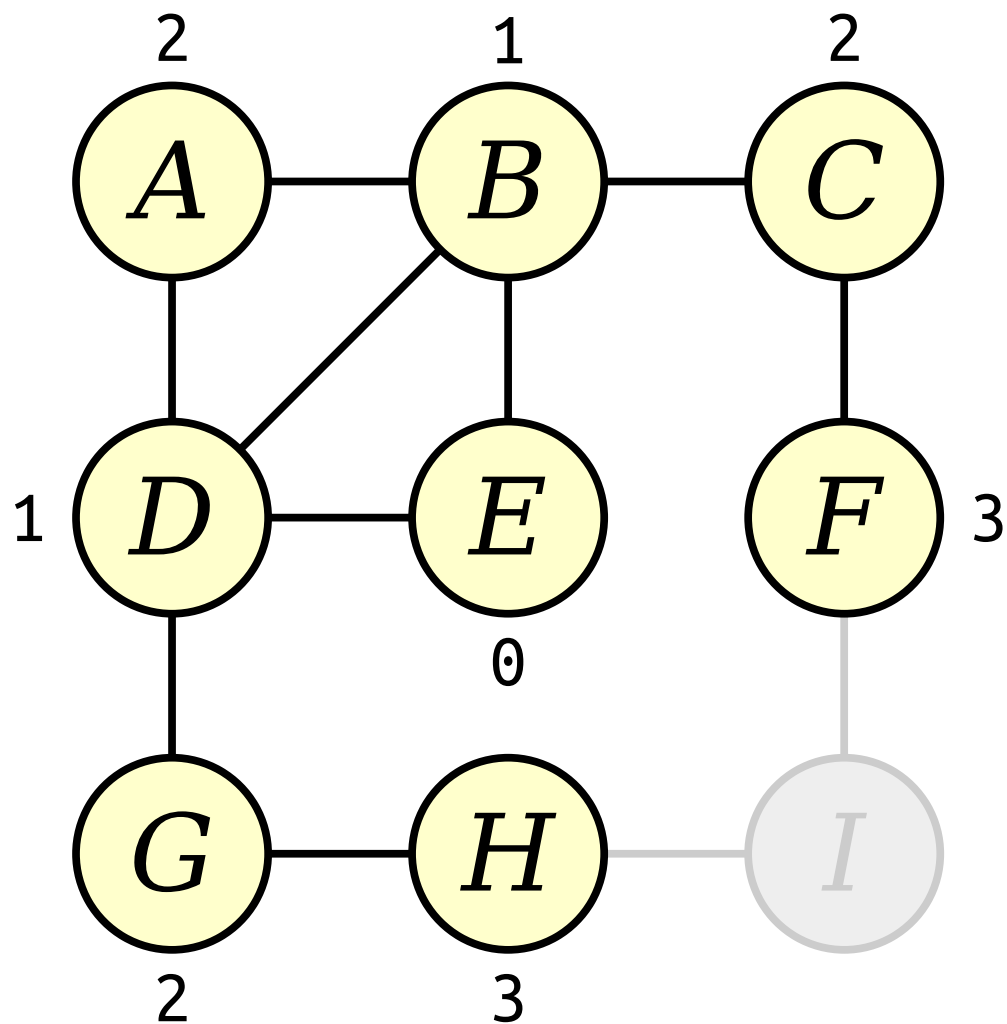
Load newly-discovered nodes into a queue.



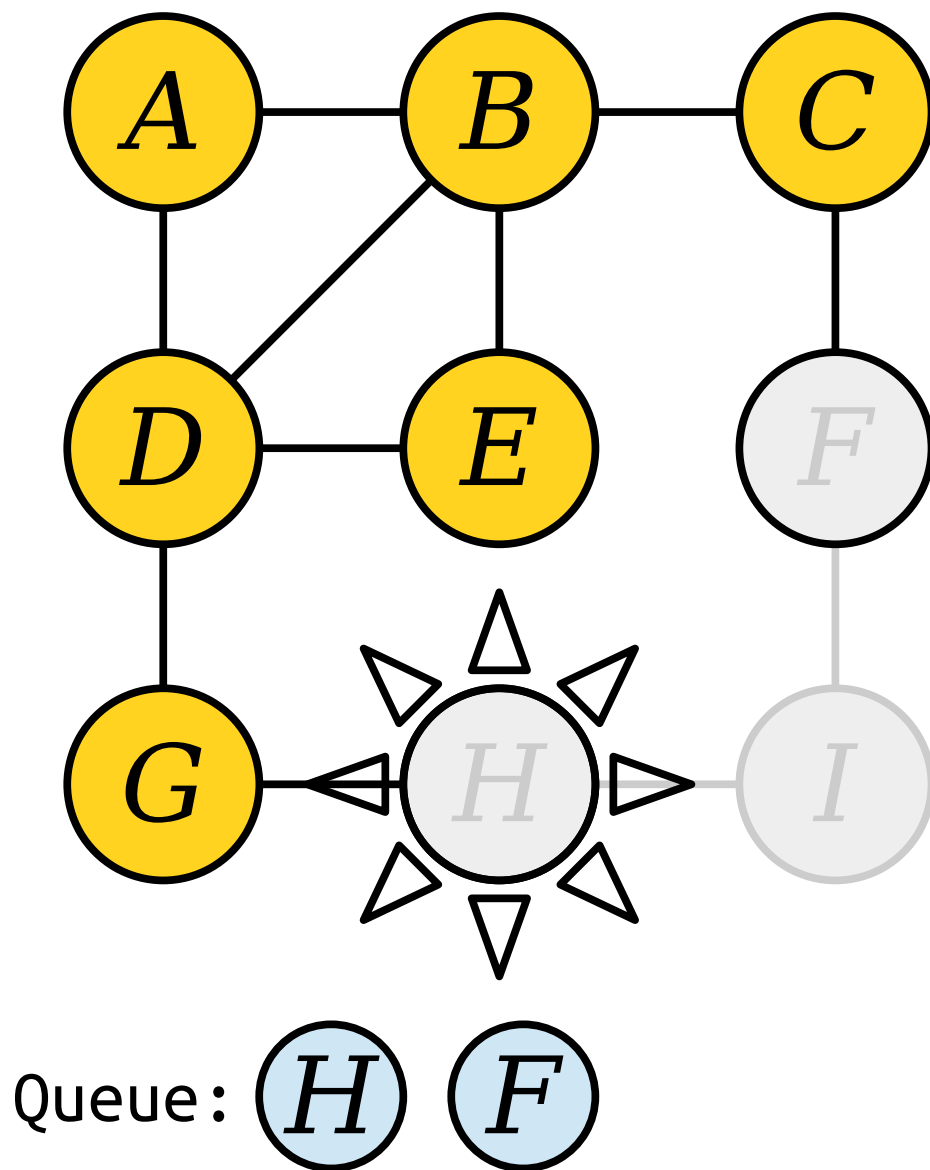
Visit nodes in ascending order of distance from the start node *E*.



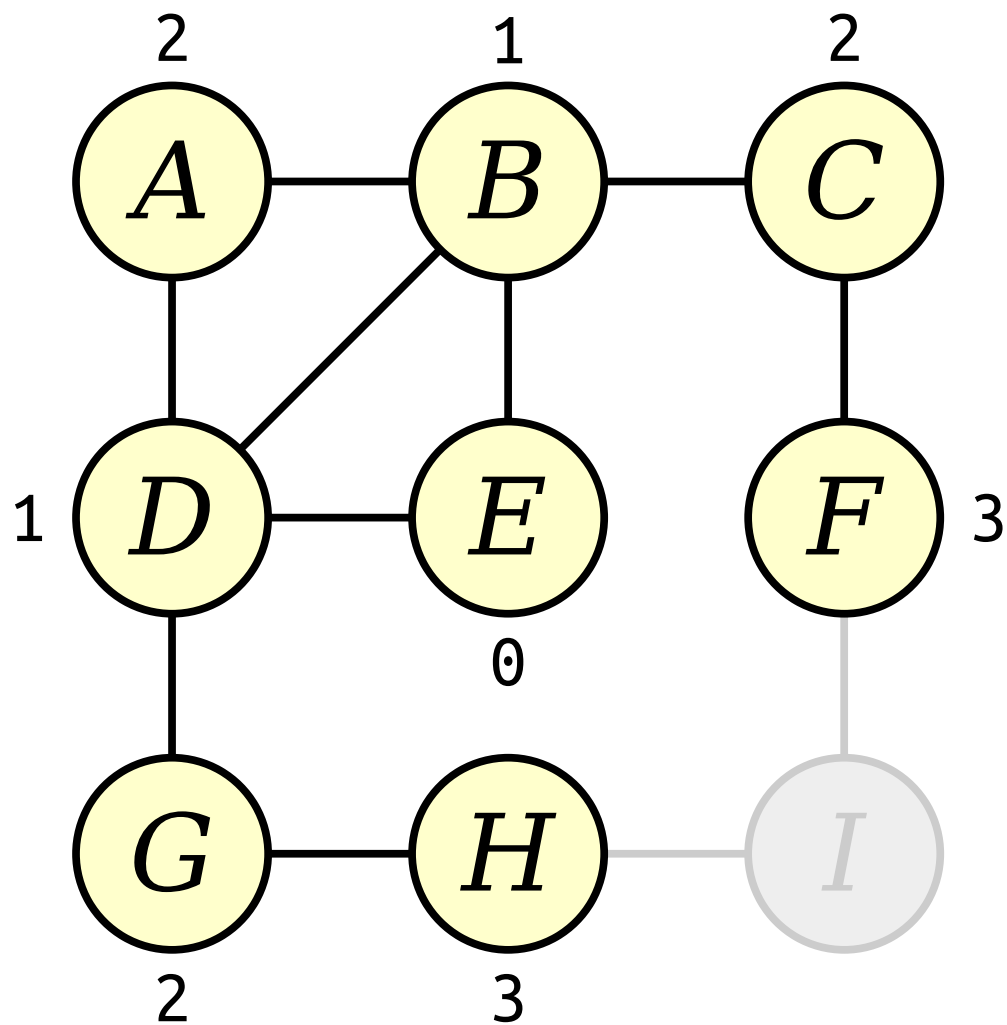
Load newly-discovered nodes into a queue.



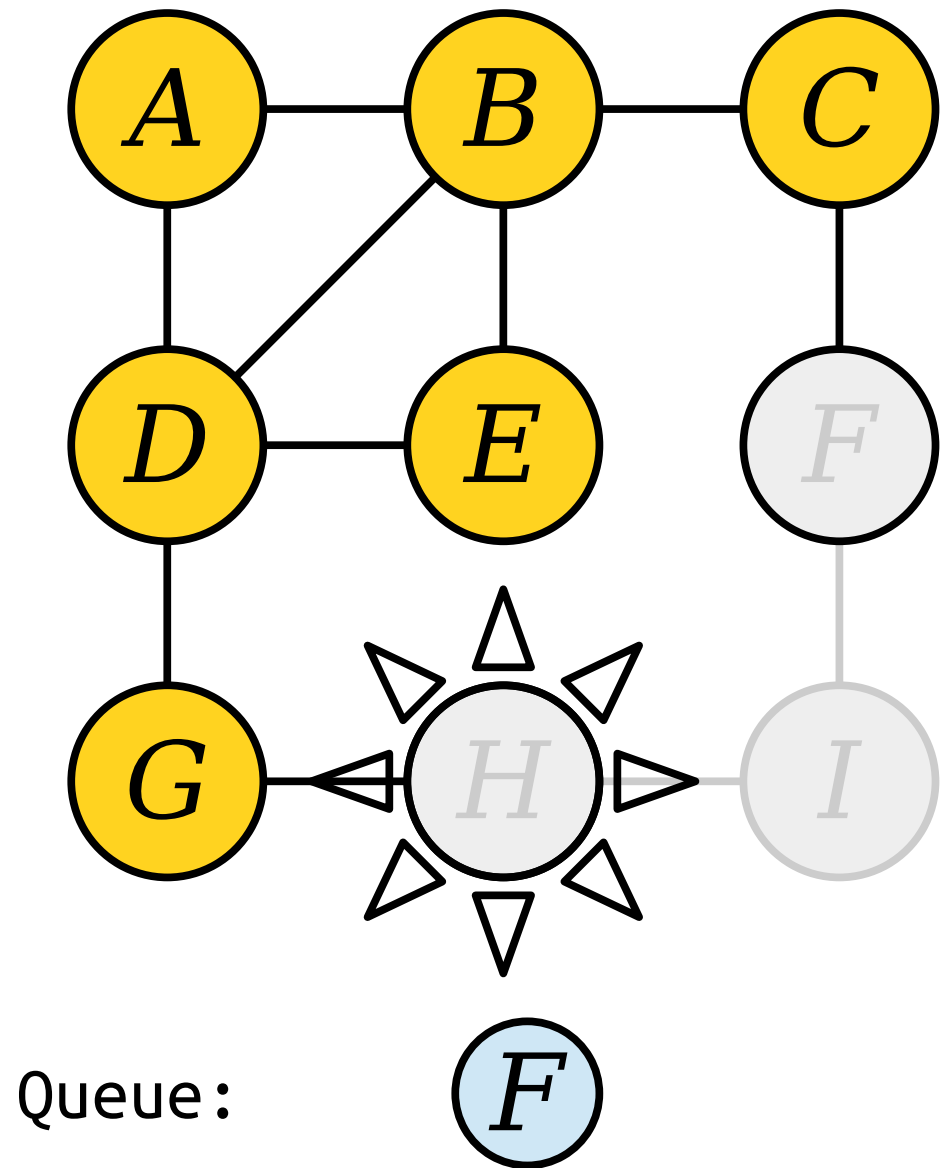
Visit nodes in ascending order of distance from the start node *E*.



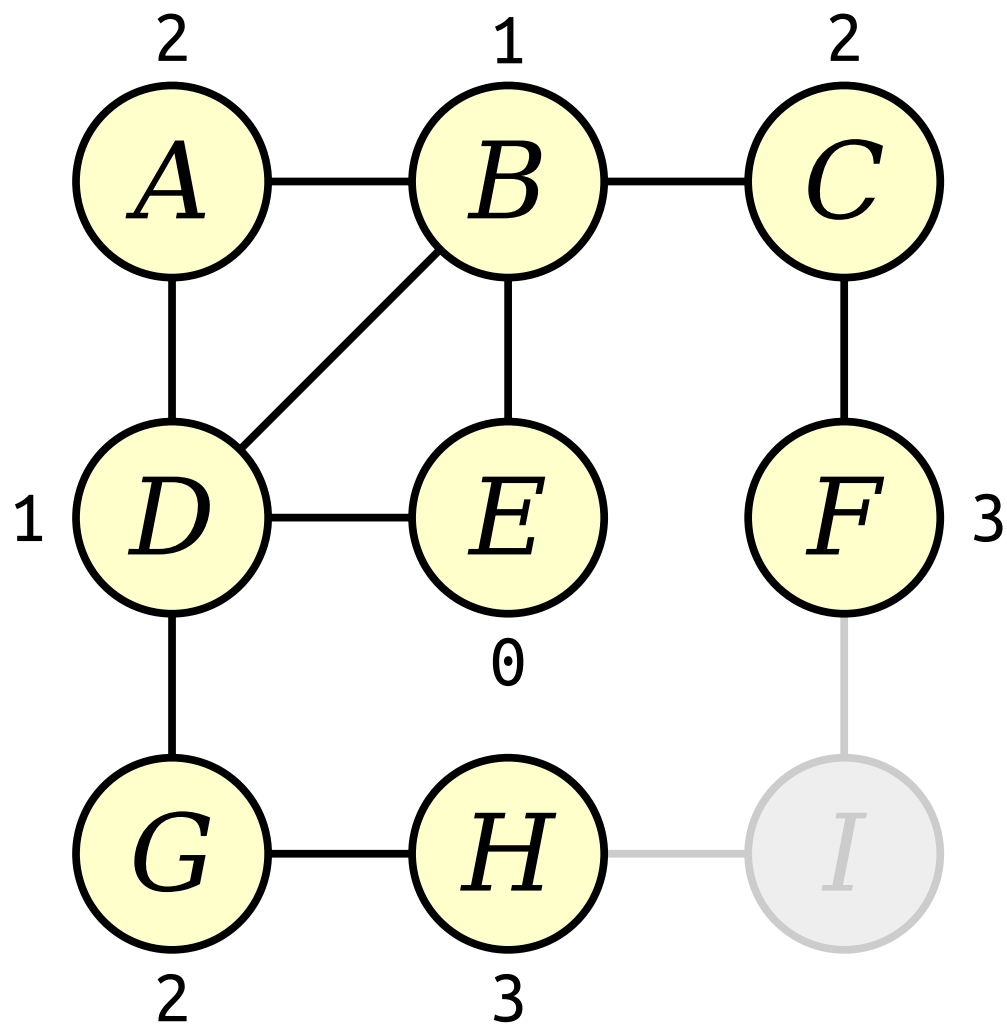
Load newly-discovered nodes into a queue.



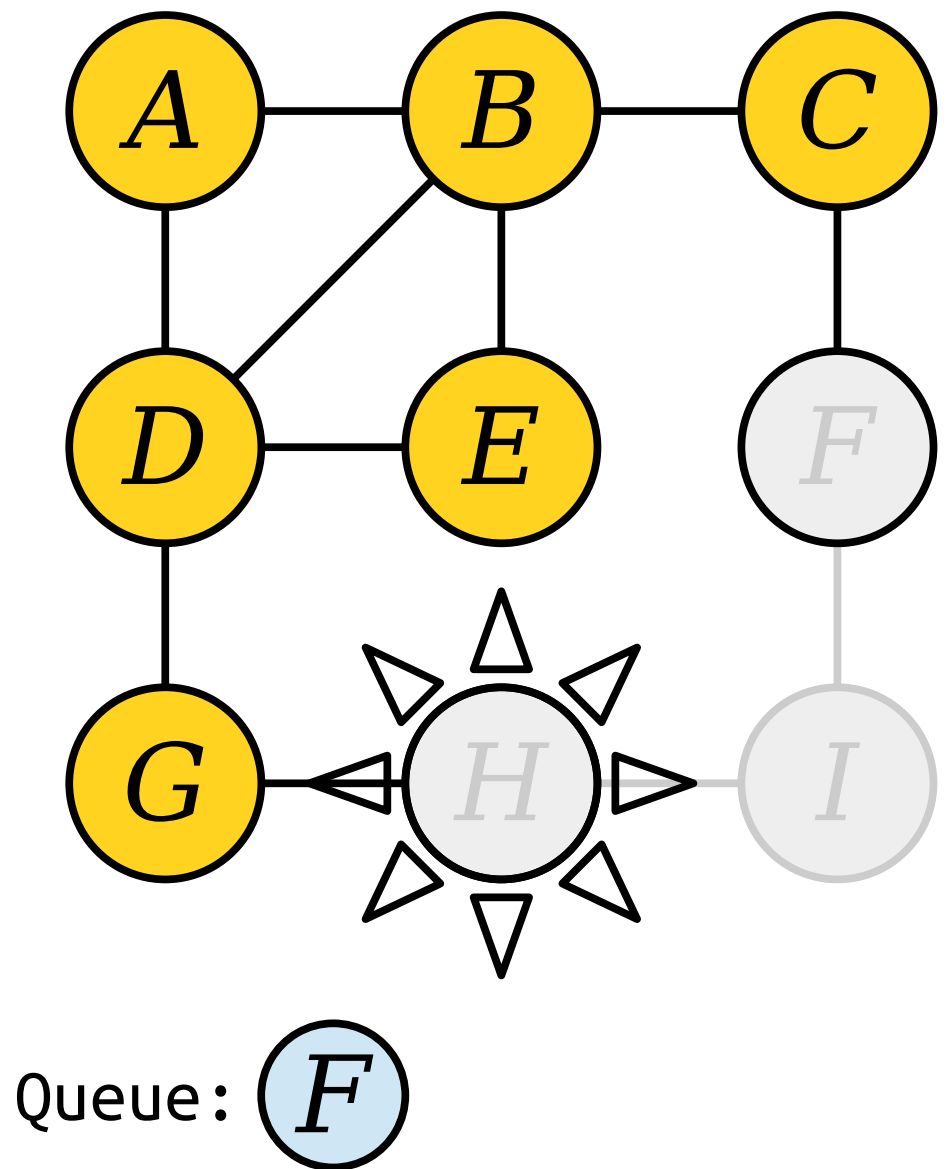
Visit nodes in ascending order of distance from the start node *E*.



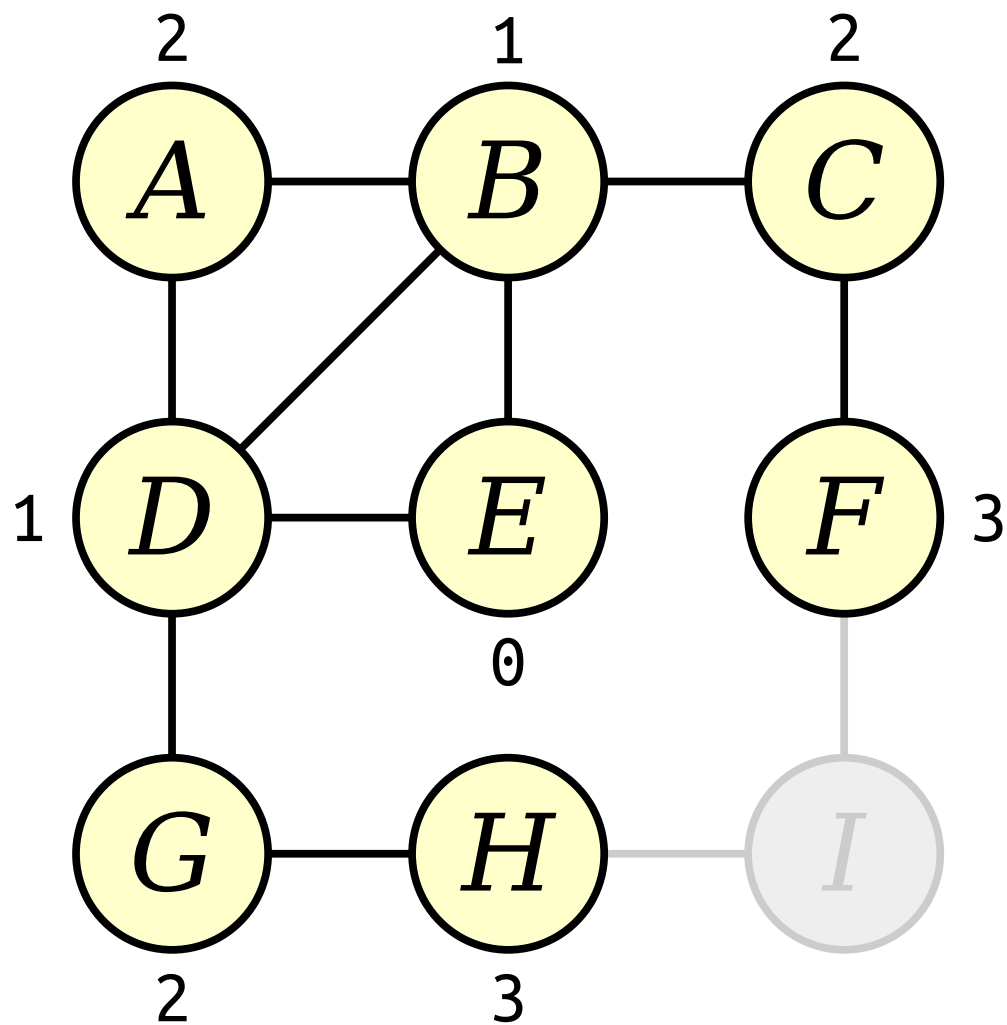
Load newly-discovered nodes into a queue.



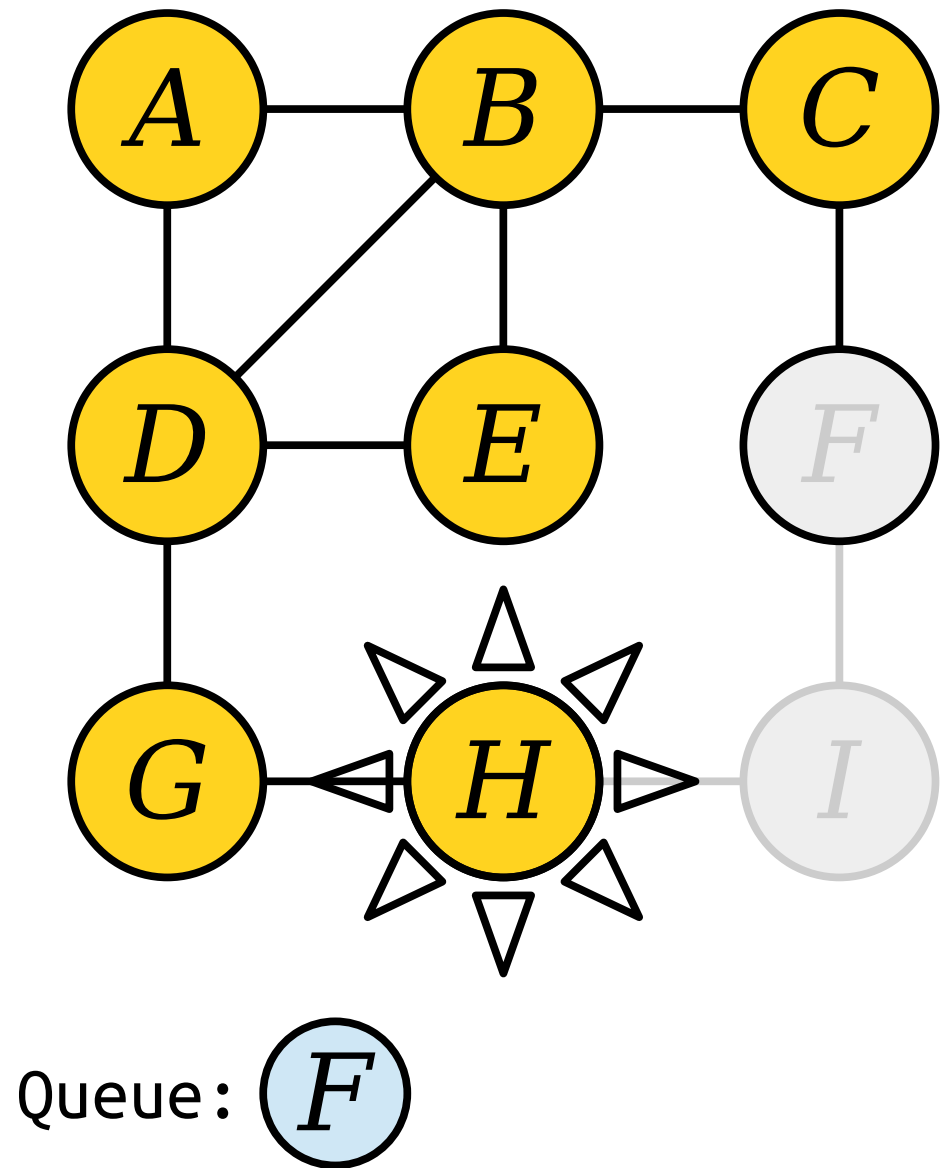
Visit nodes in ascending order of distance from the start node *E*.



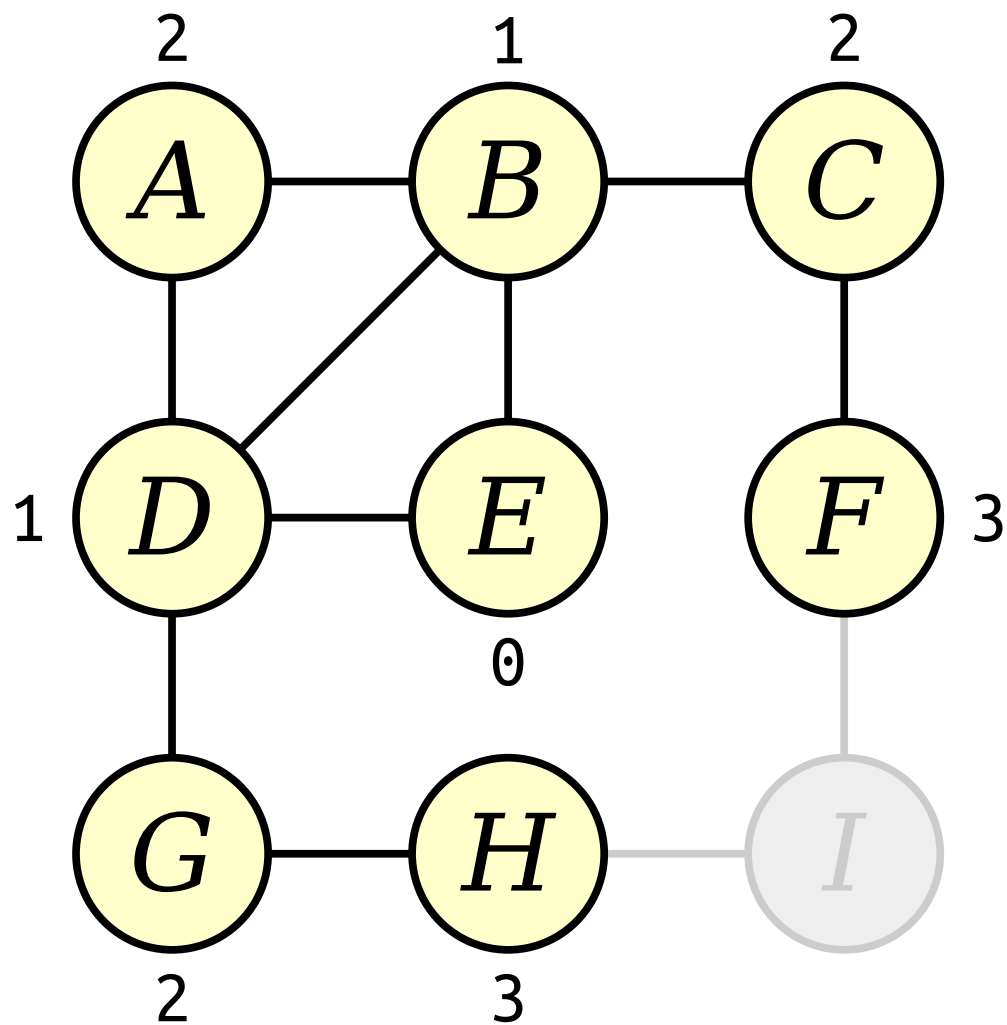
Load newly-discovered nodes into a queue.



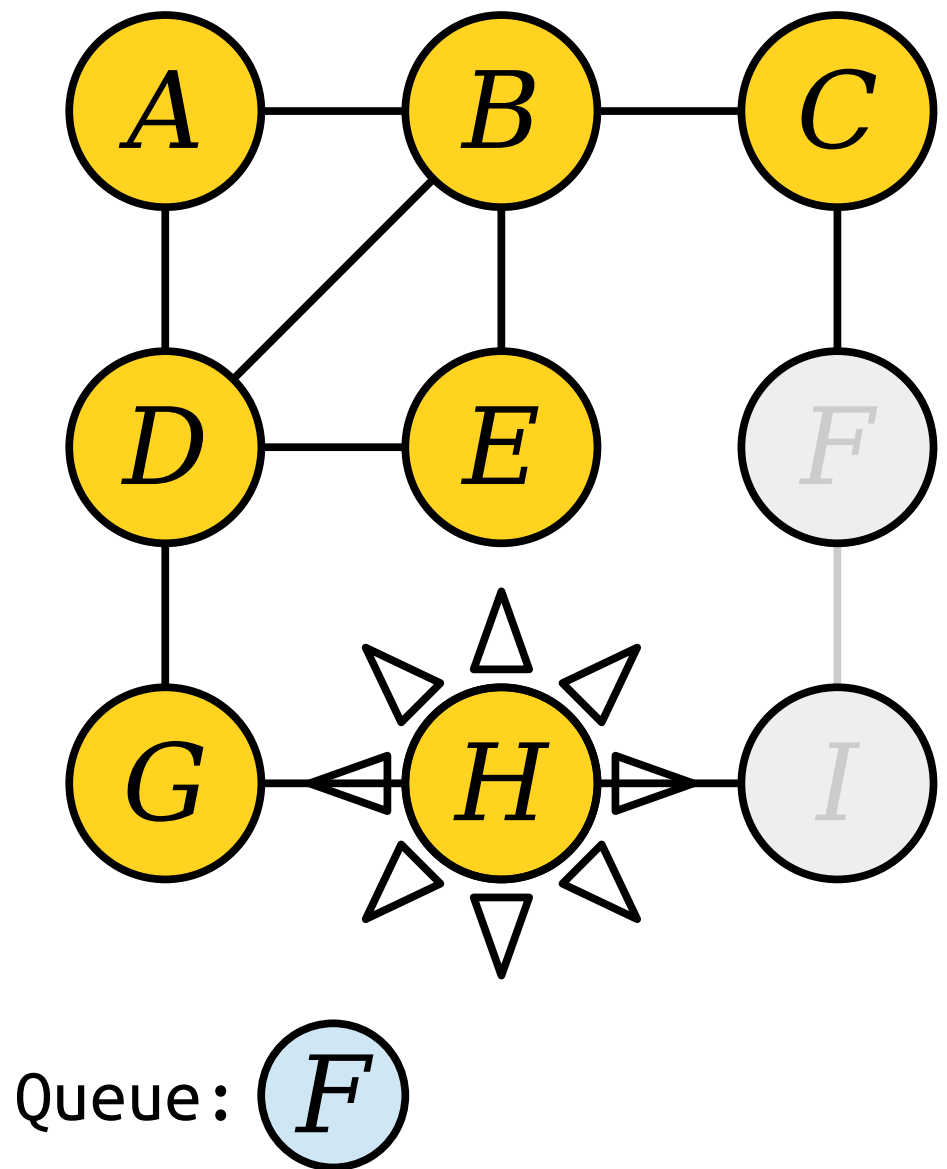
Visit nodes in ascending order of distance from the start node *E*.



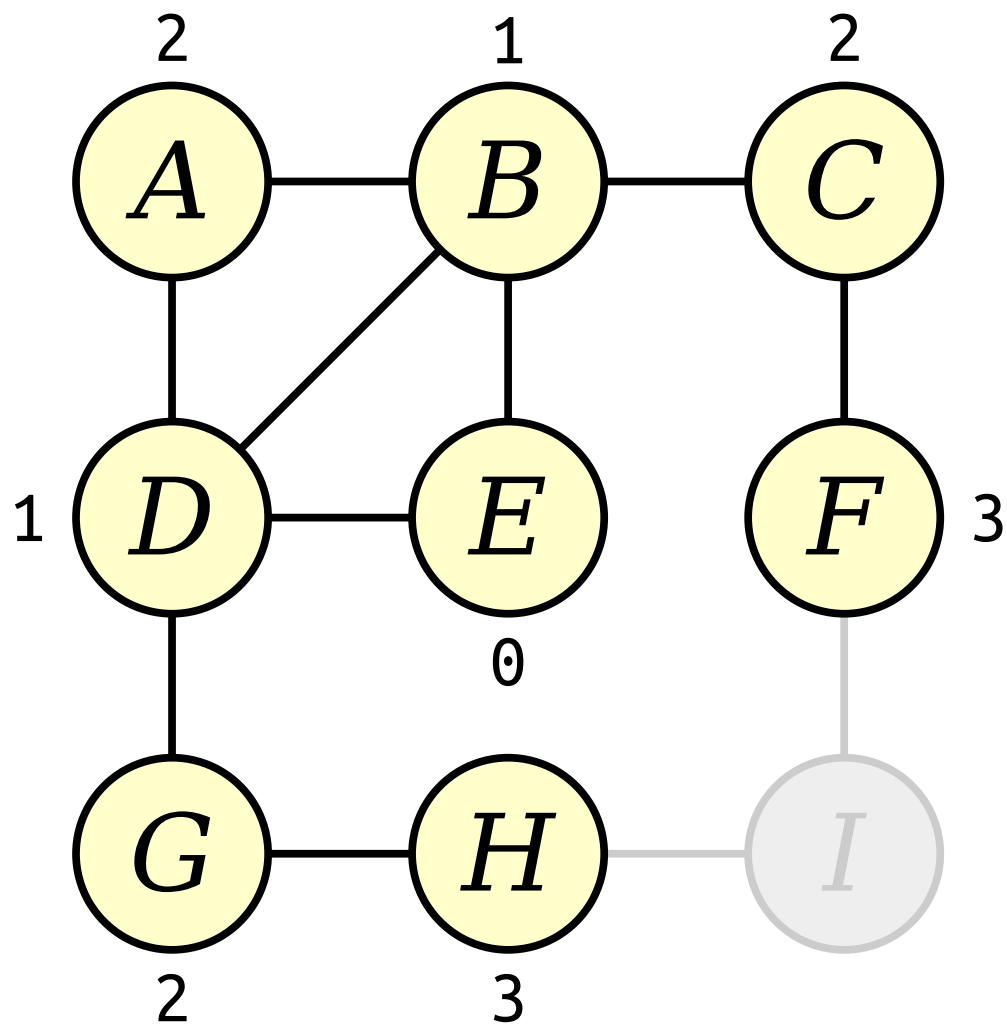
Load newly-discovered nodes into a queue.



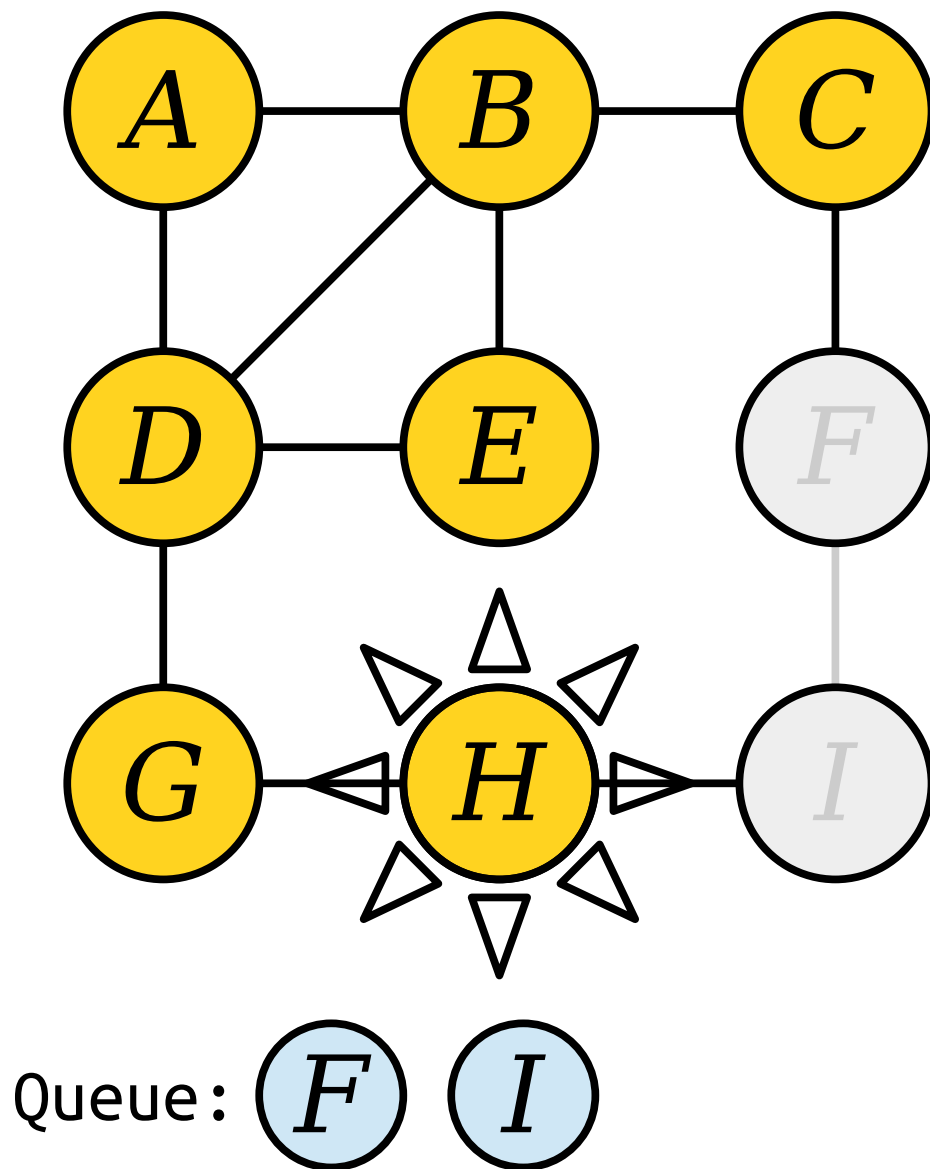
Visit nodes in ascending order of distance from the start node *E*.



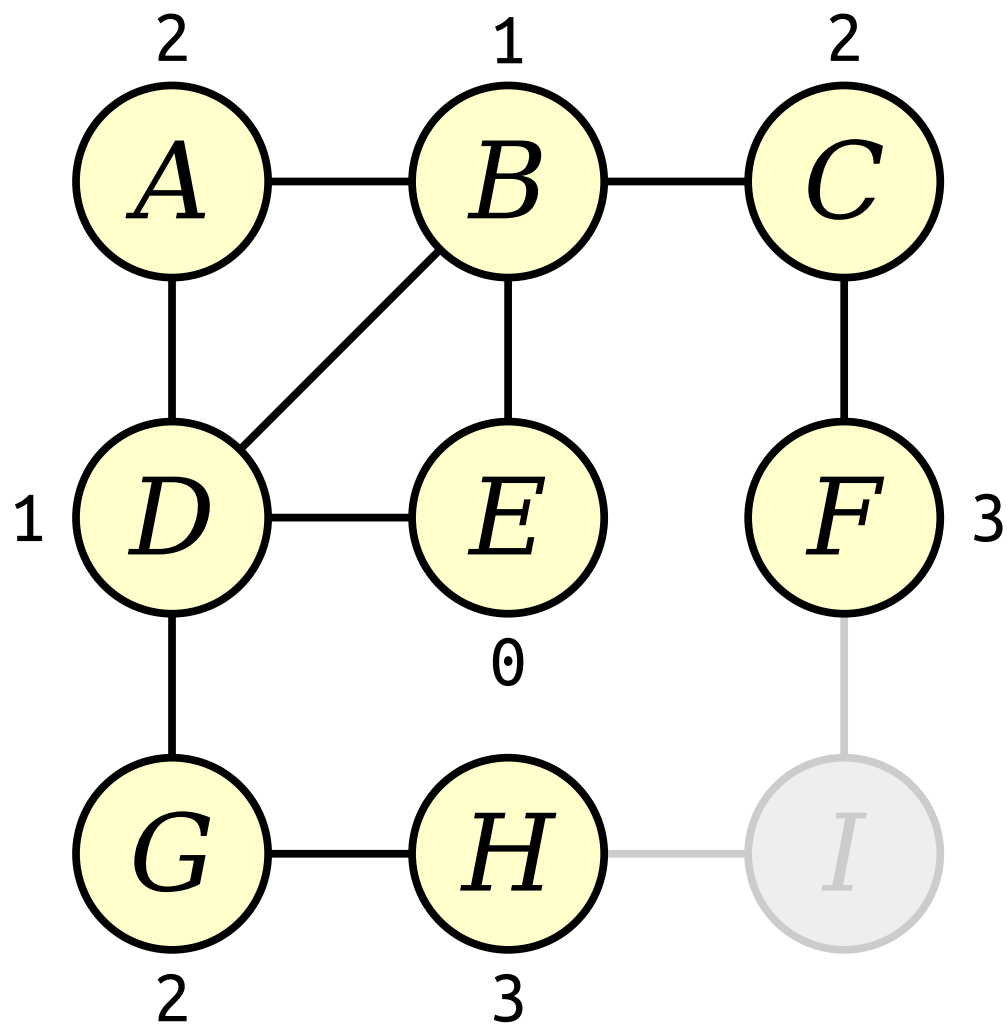
Load newly-discovered nodes into a queue.



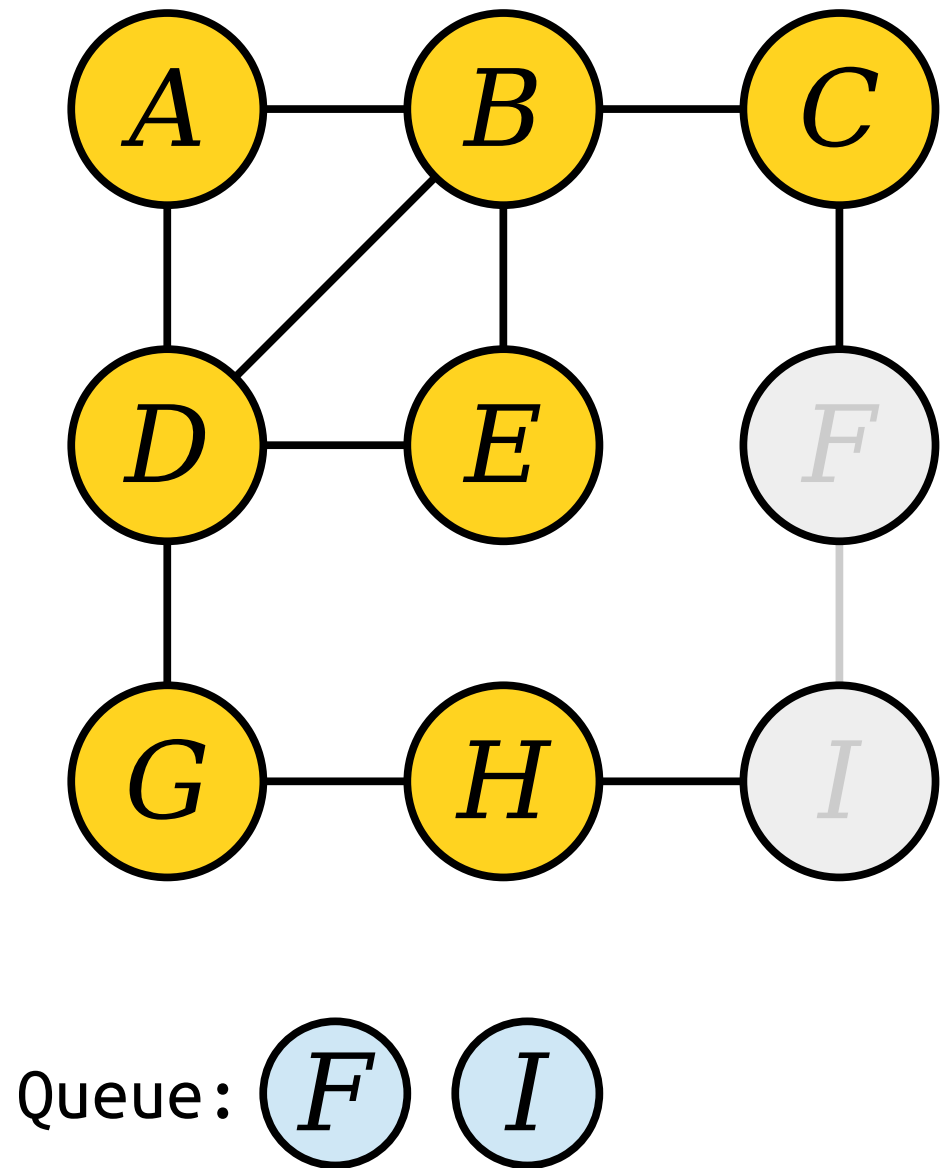
Visit nodes in ascending order of distance from the start node *E*.



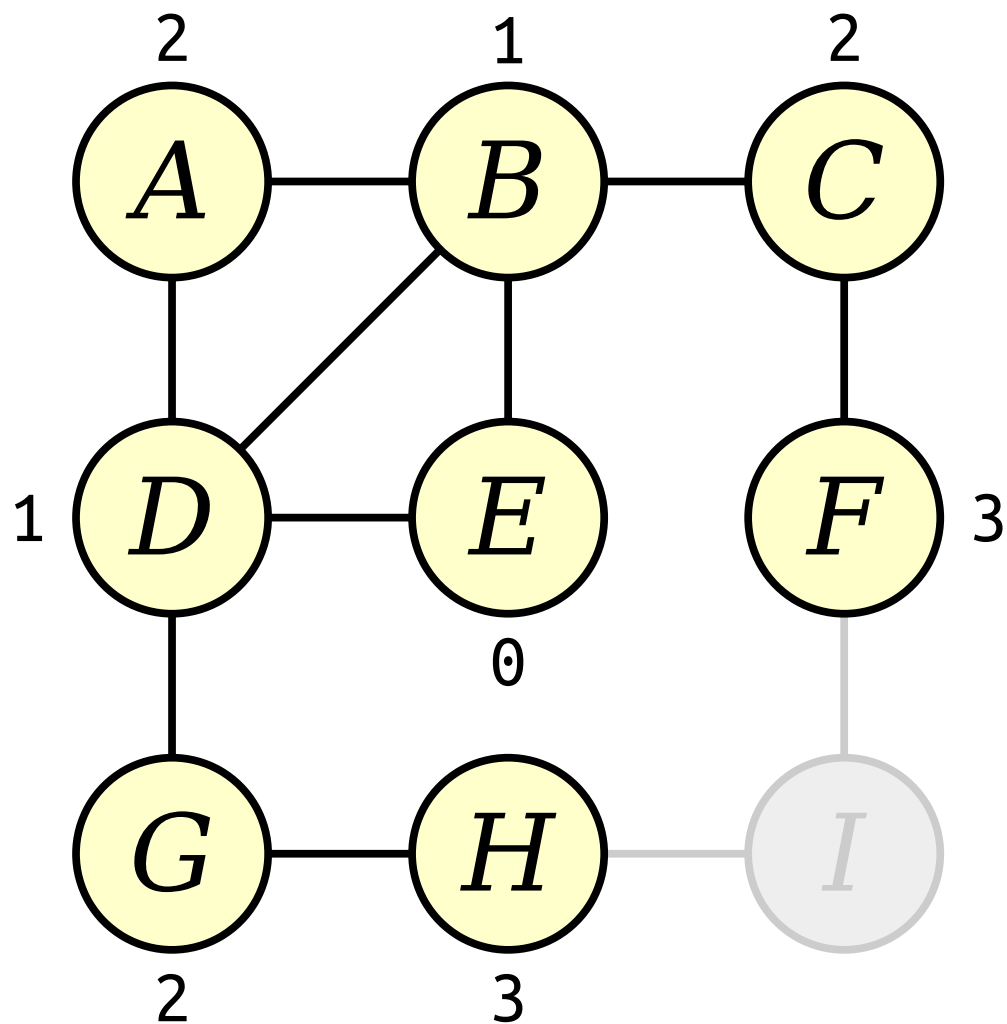
Load newly-discovered nodes into a queue.



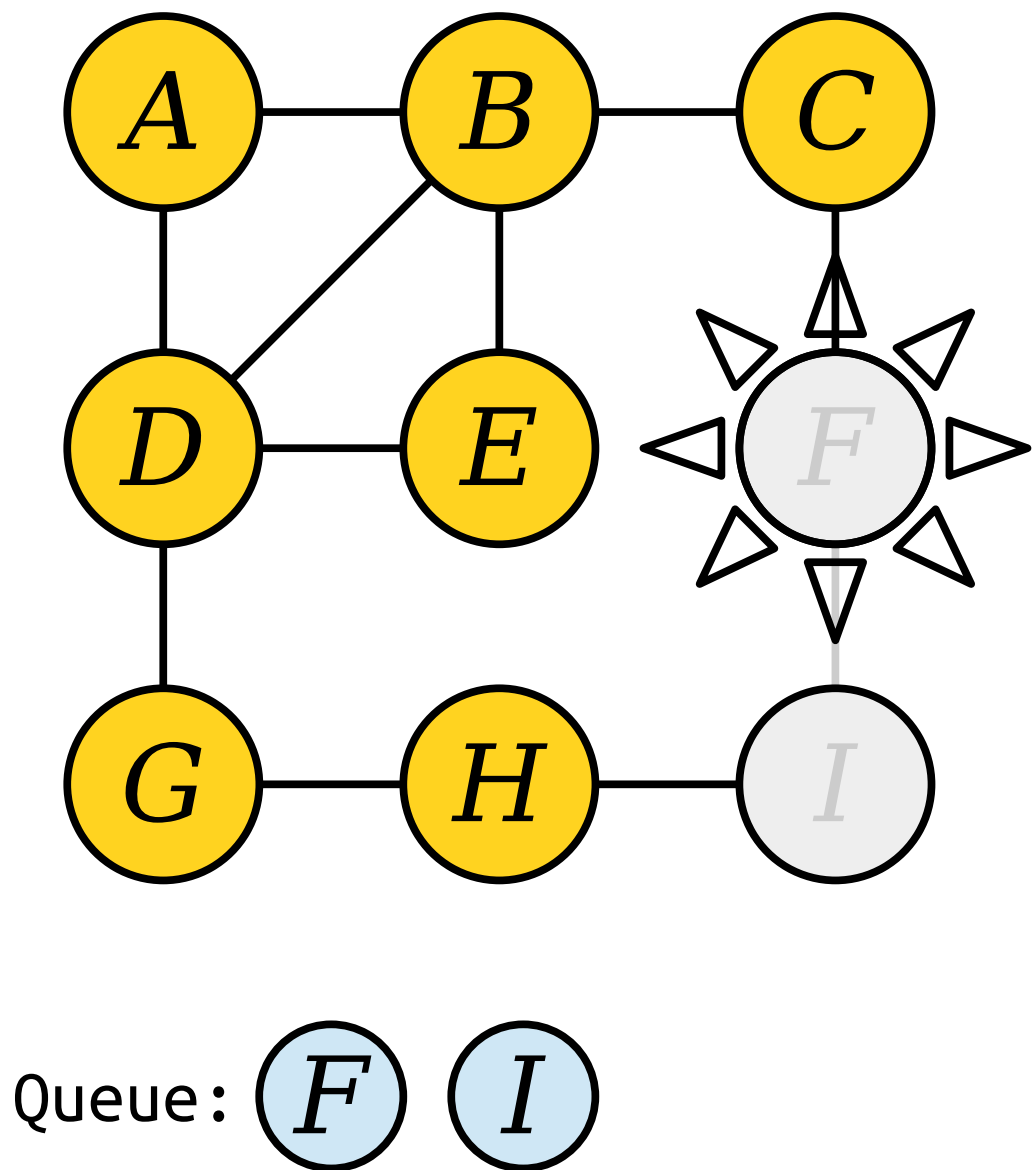
Visit nodes in ascending order of distance from the start node *E*.



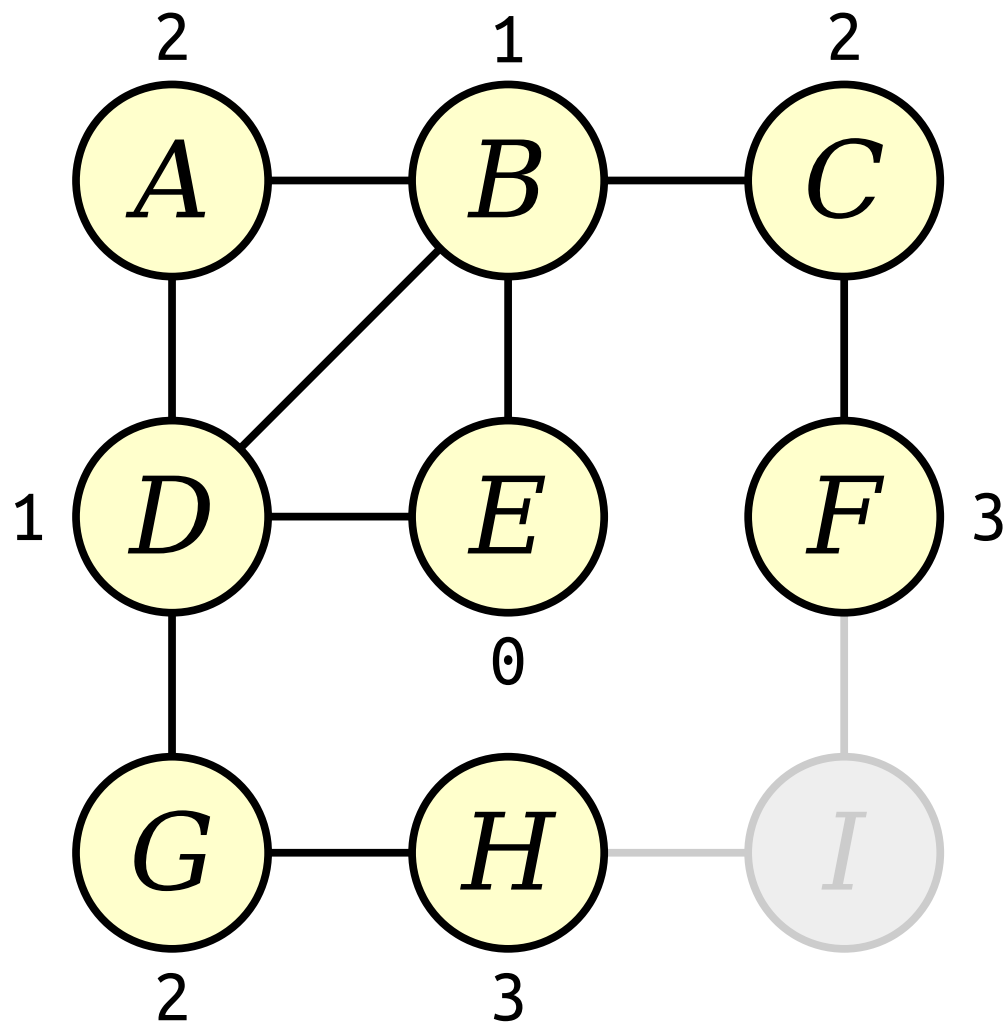
Load newly-discovered nodes into a queue.



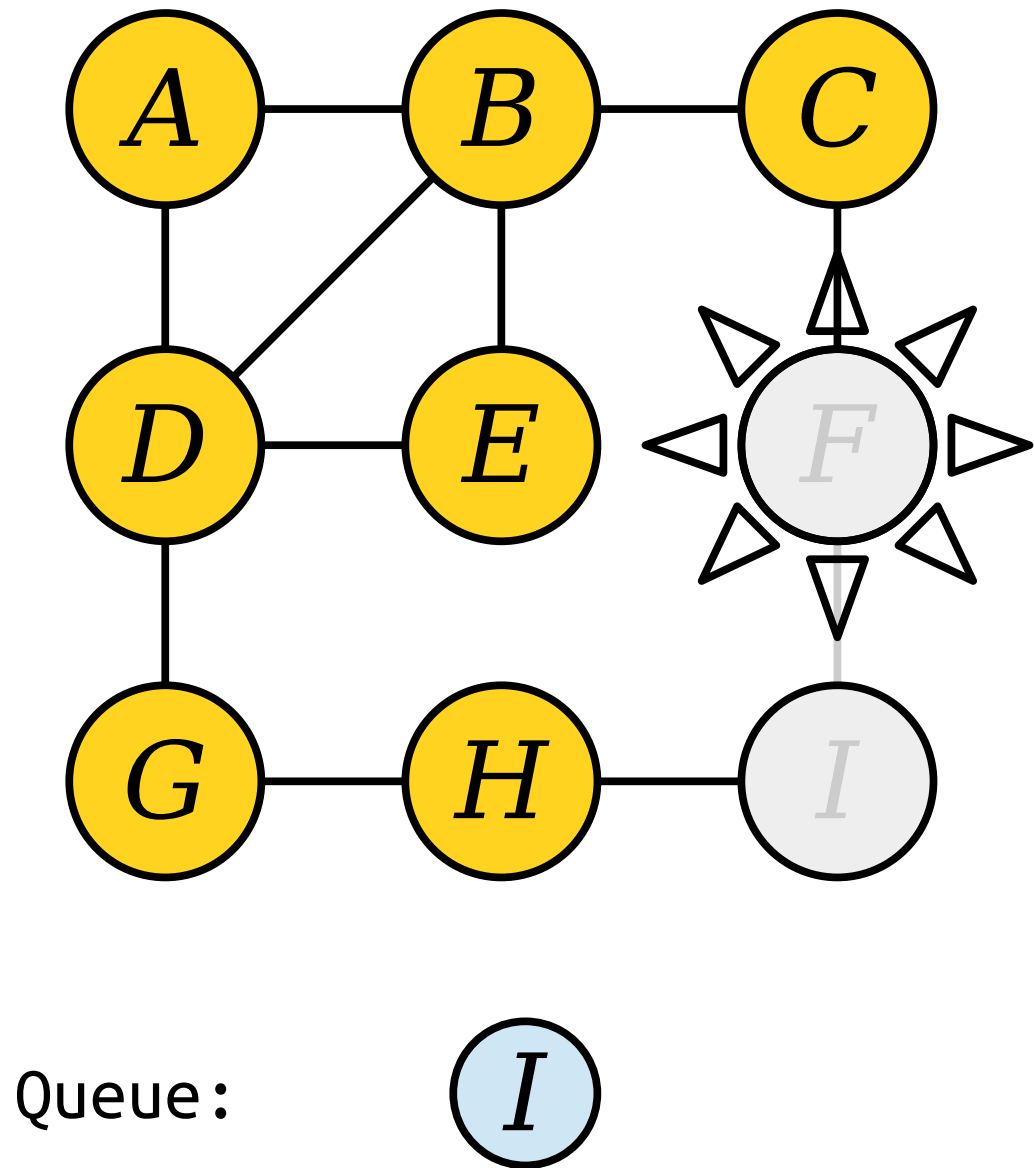
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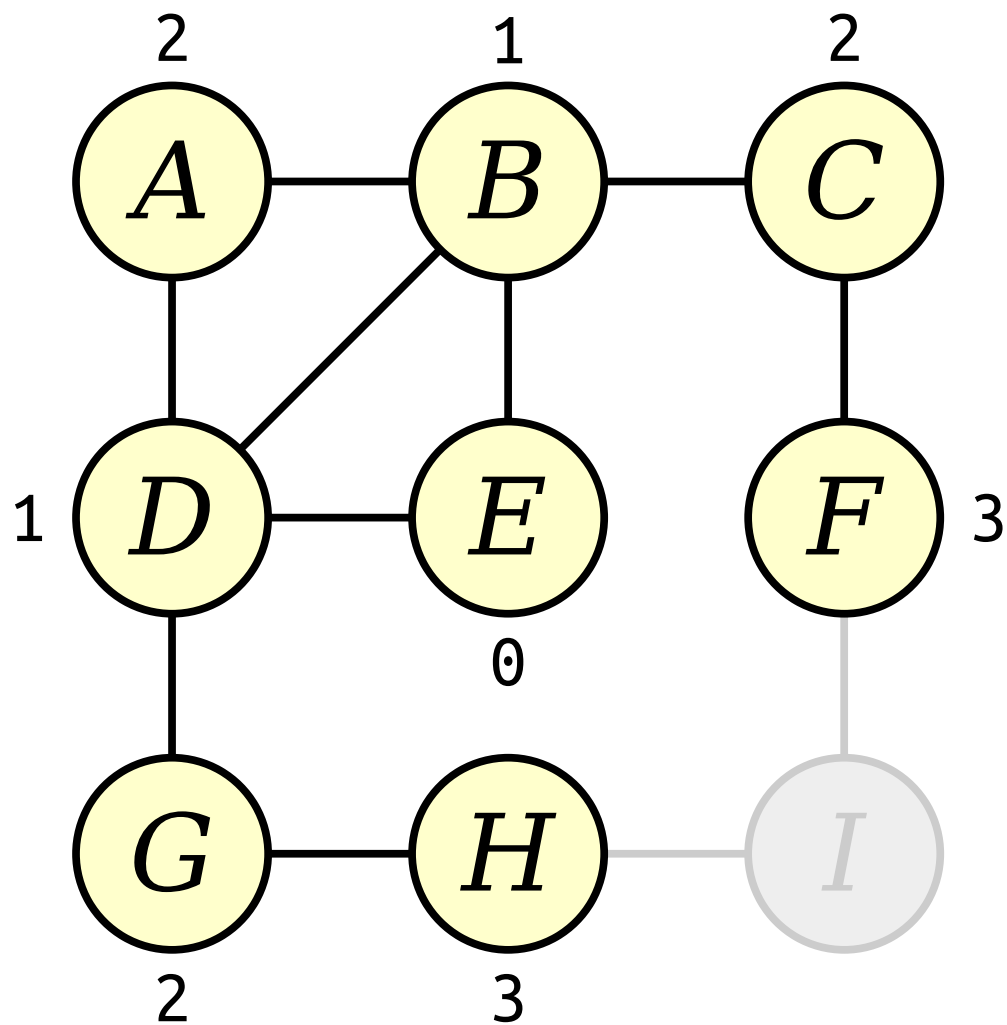
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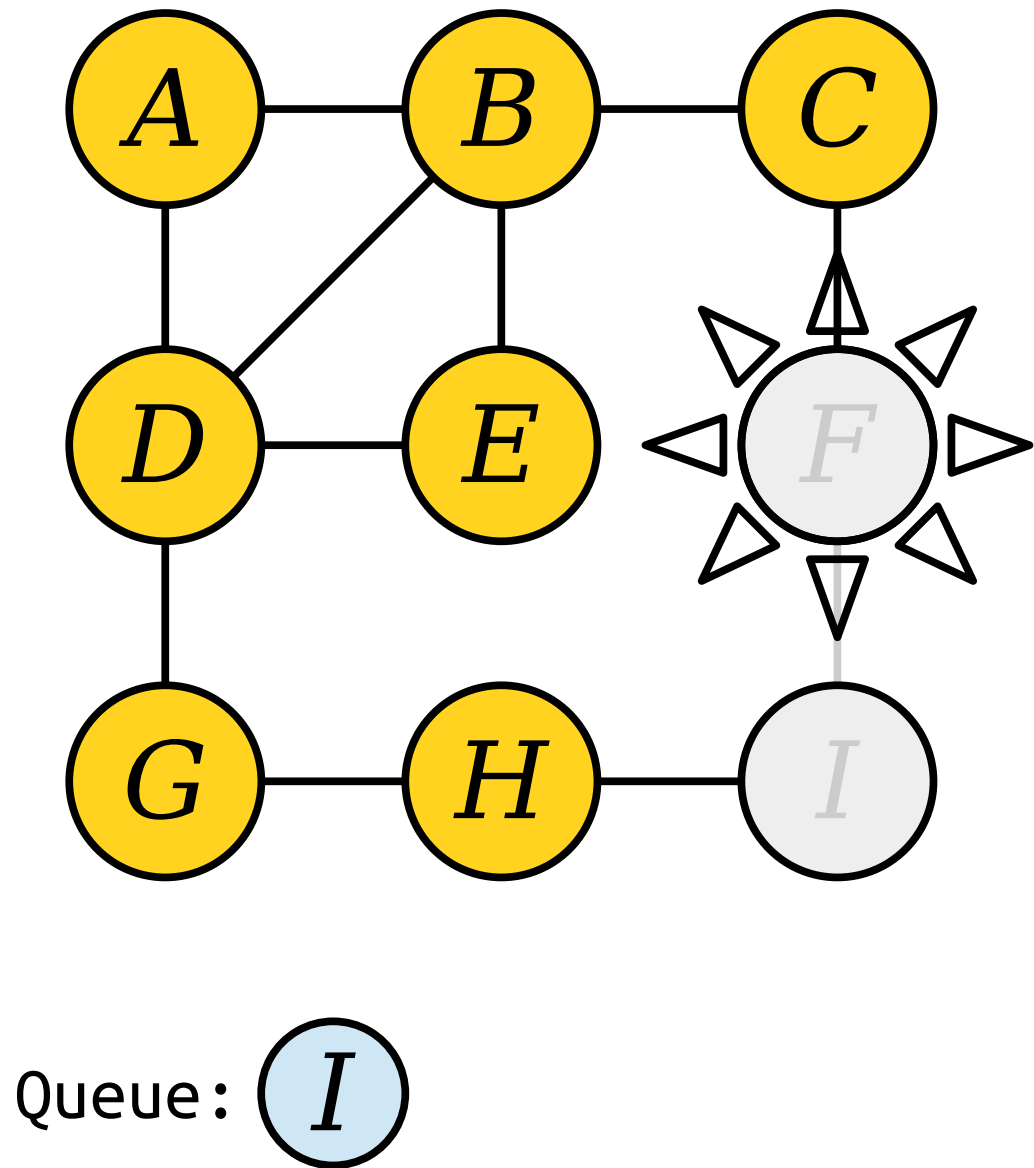
Visit nodes in ascending order of distance from the start node E .



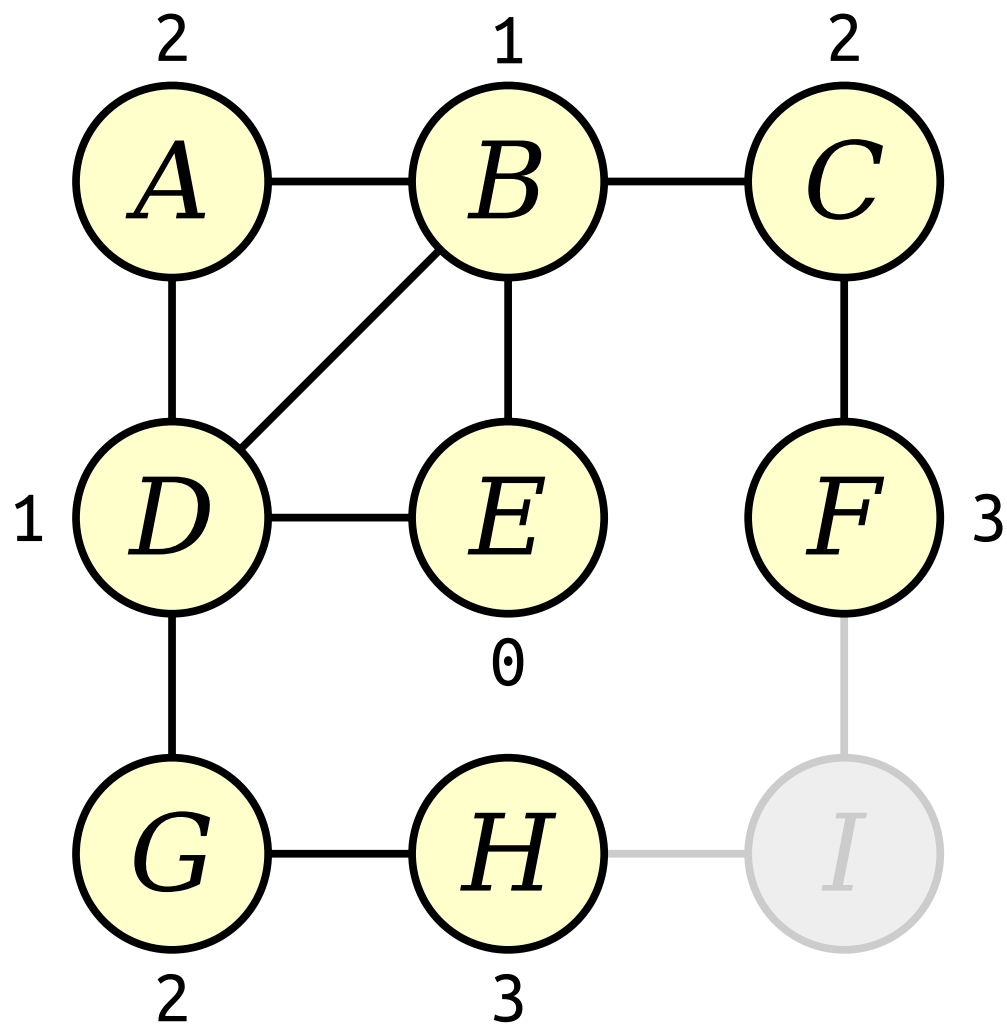
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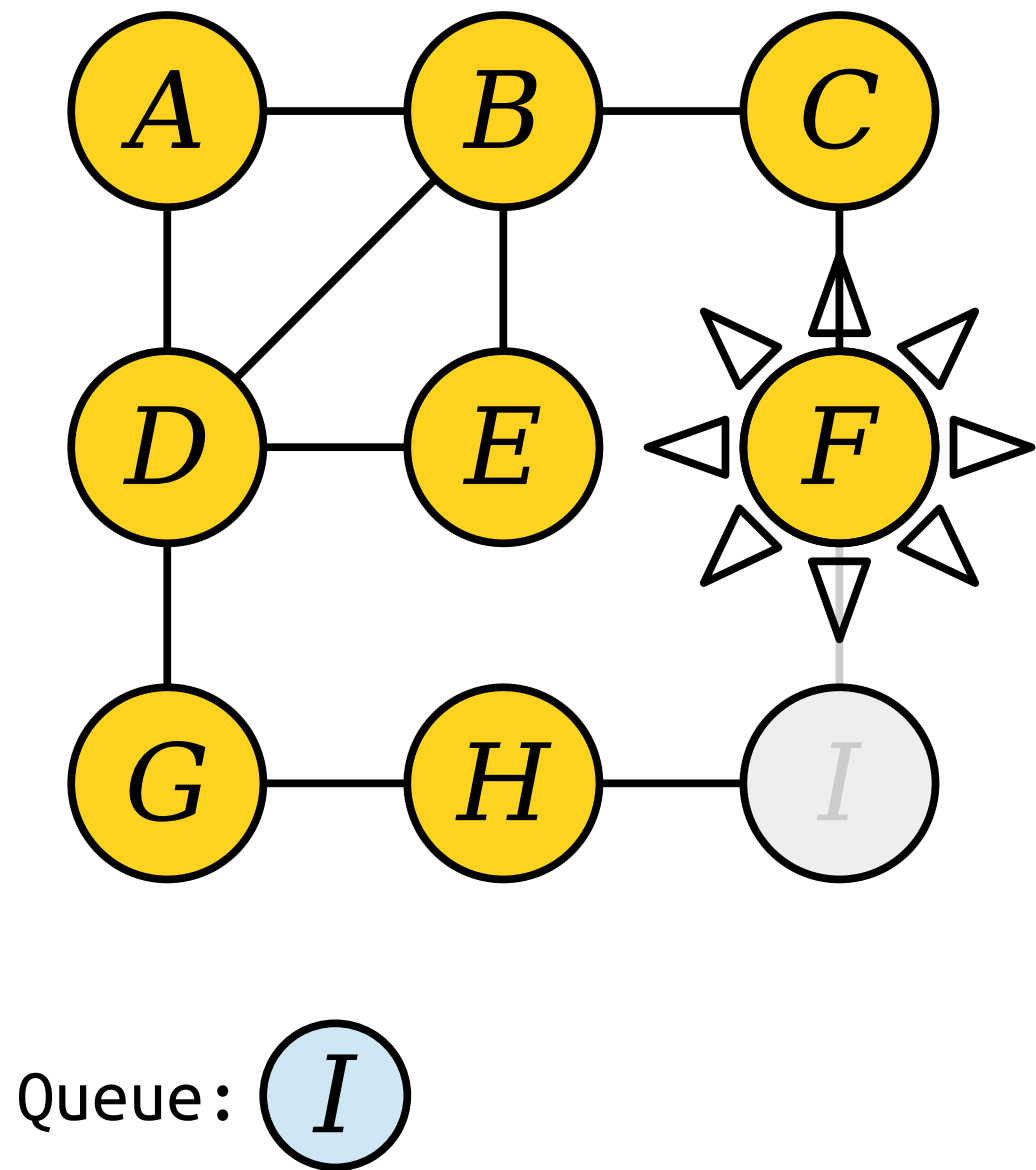
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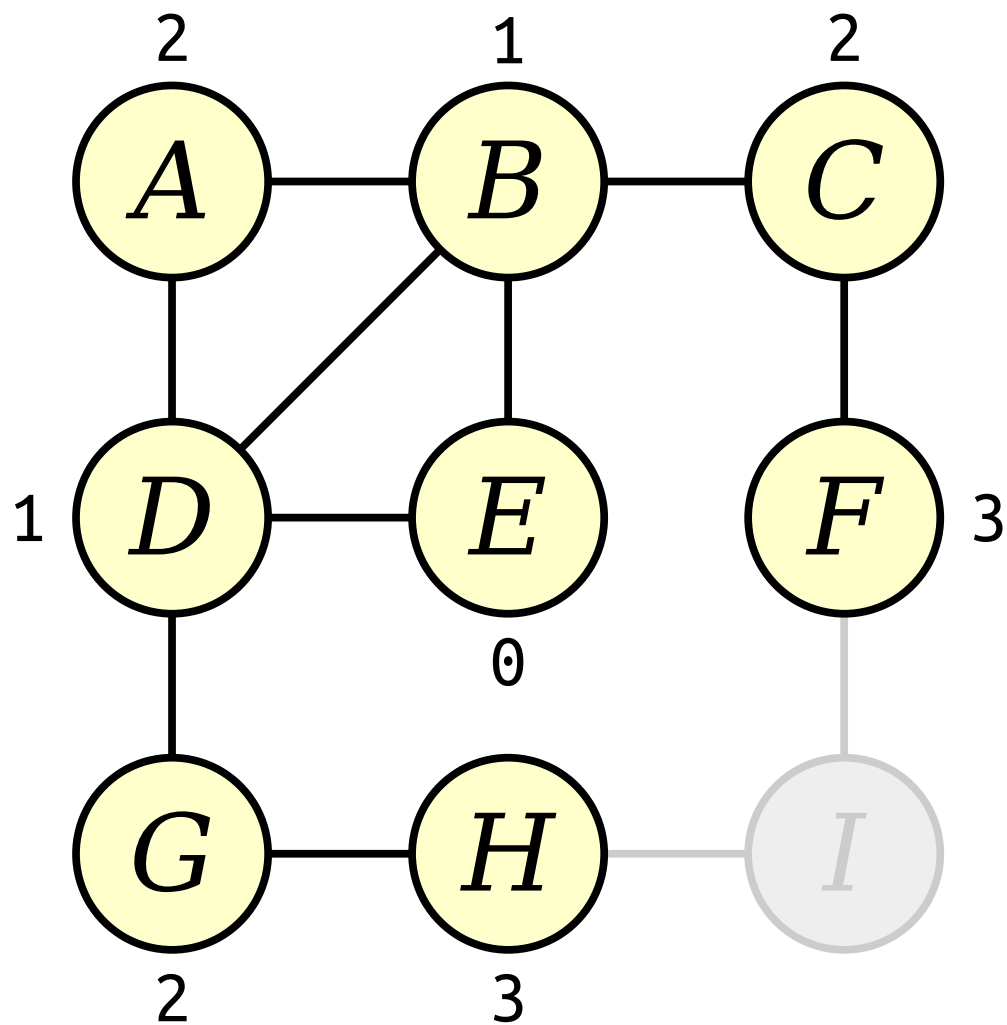
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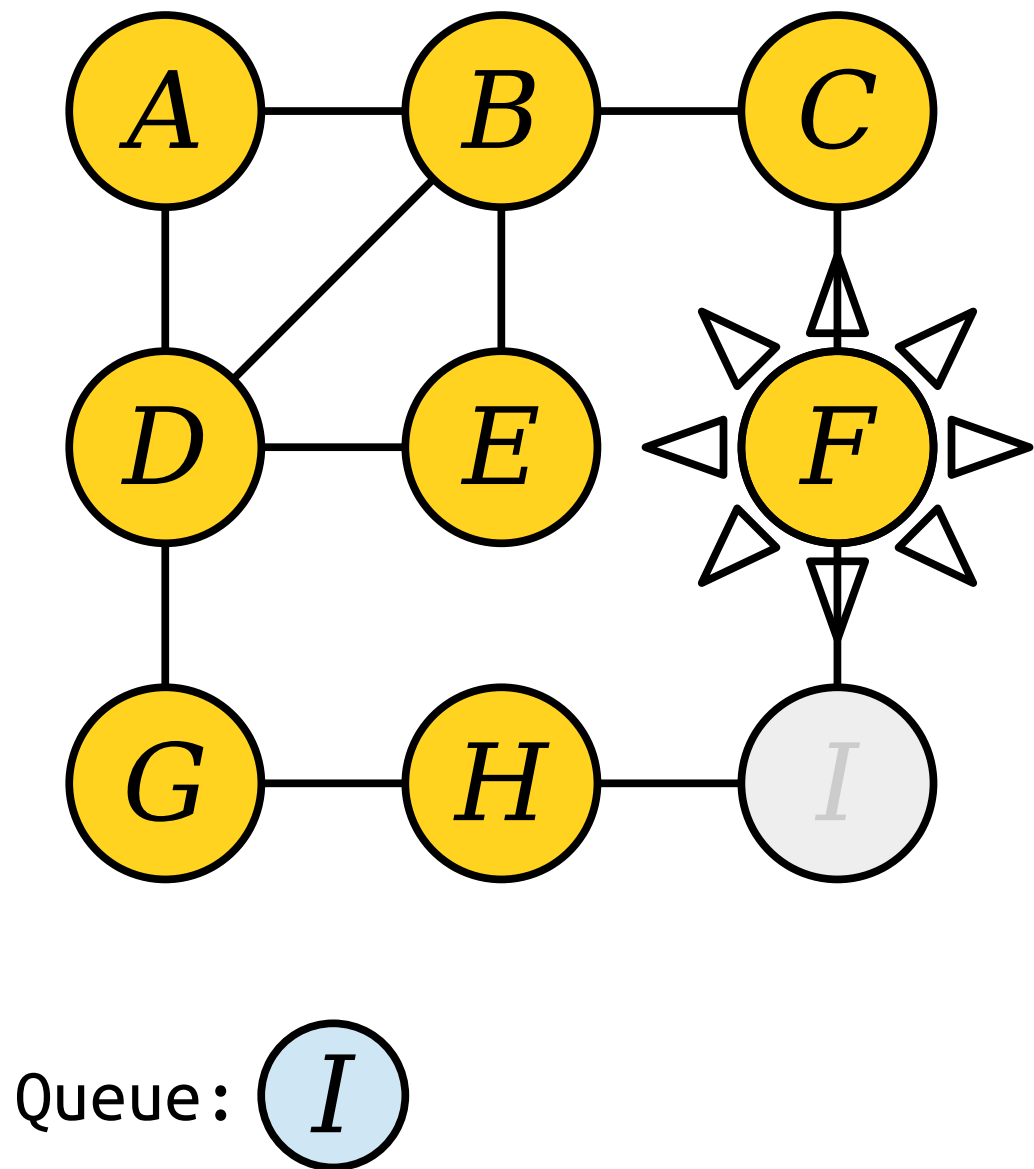
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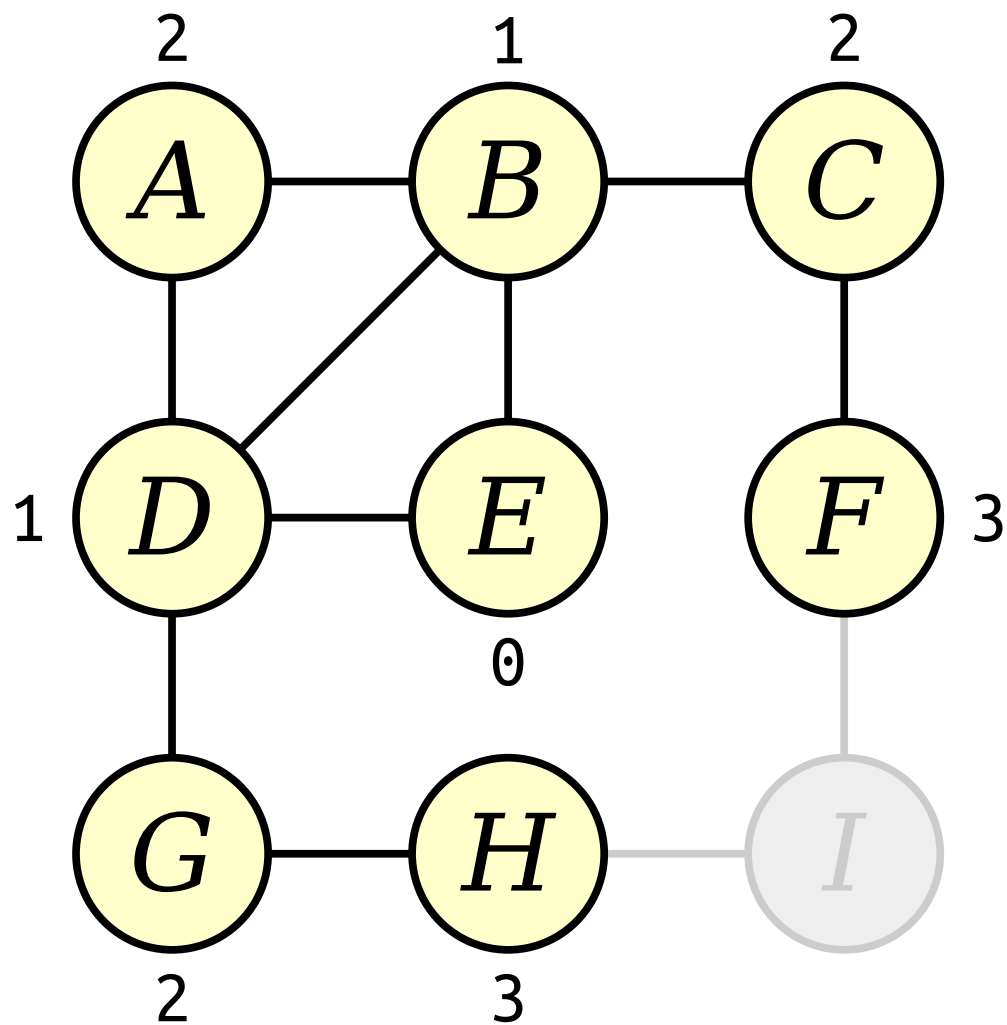
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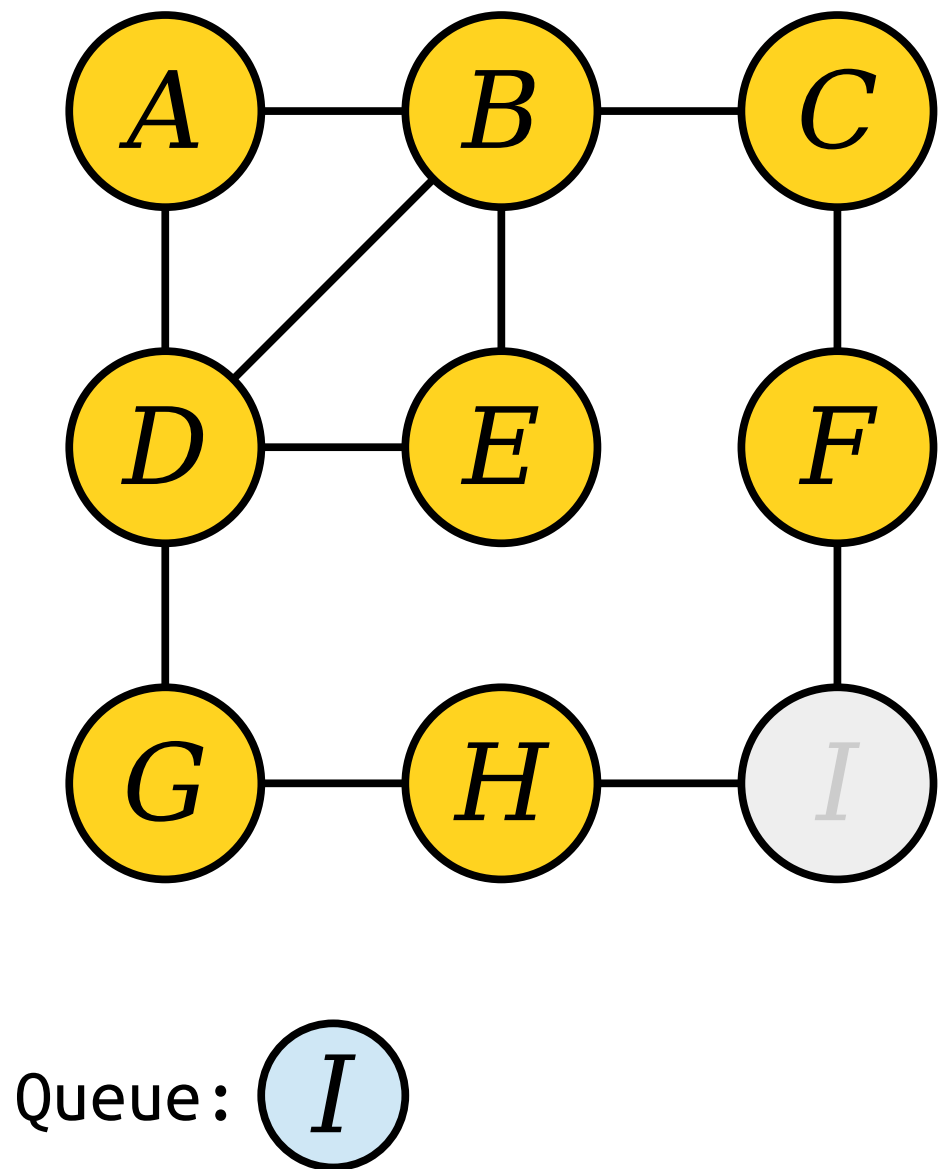
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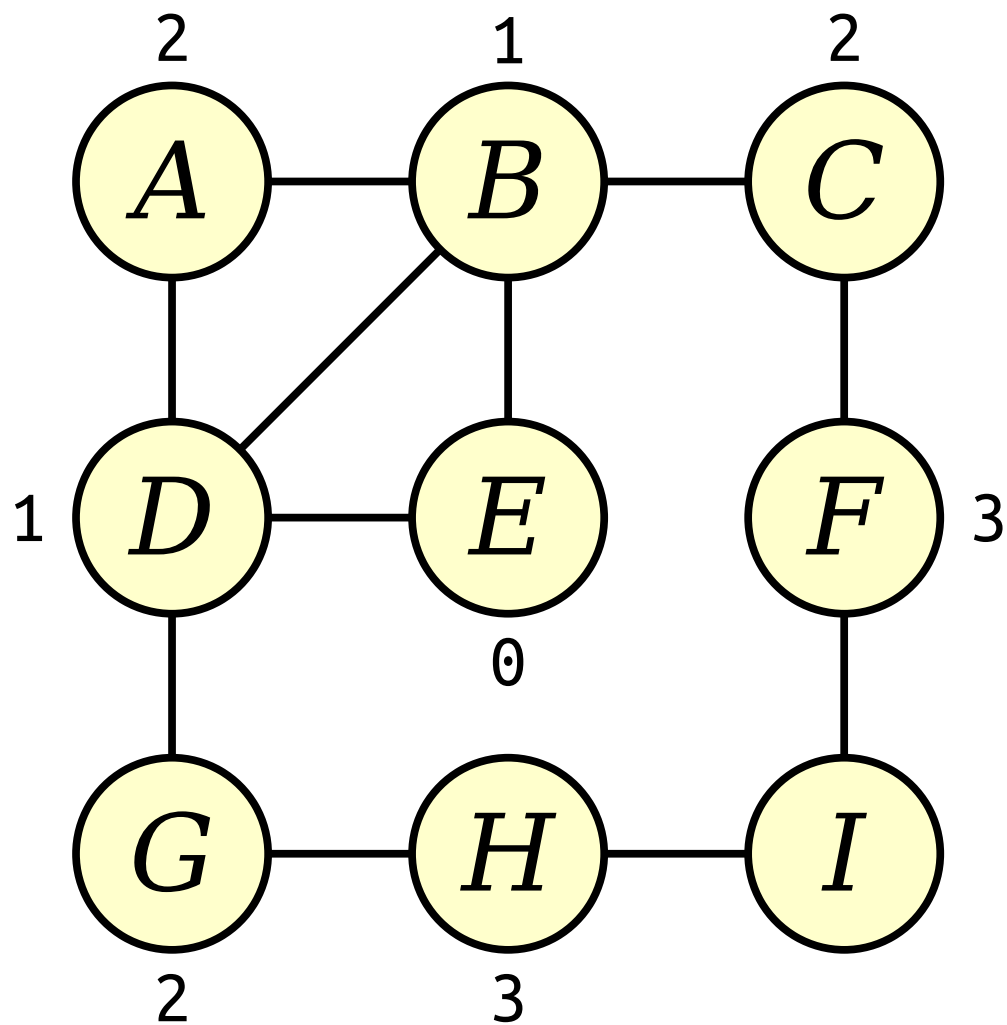
Load newly-discovered nodes into a queue.



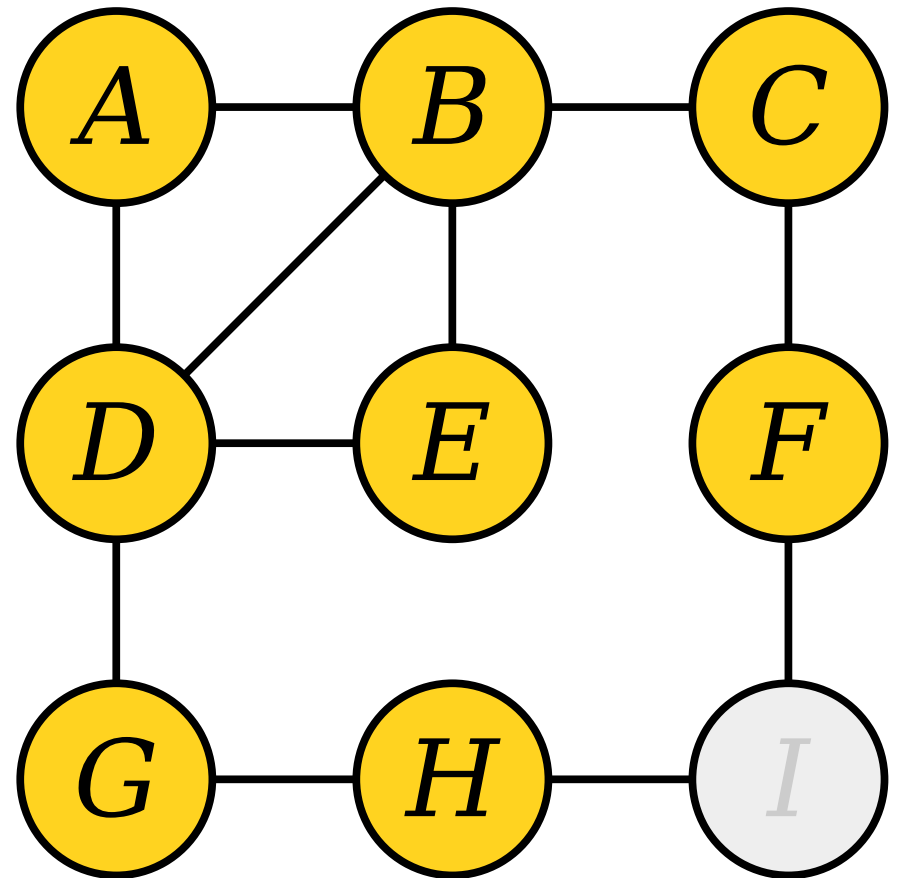
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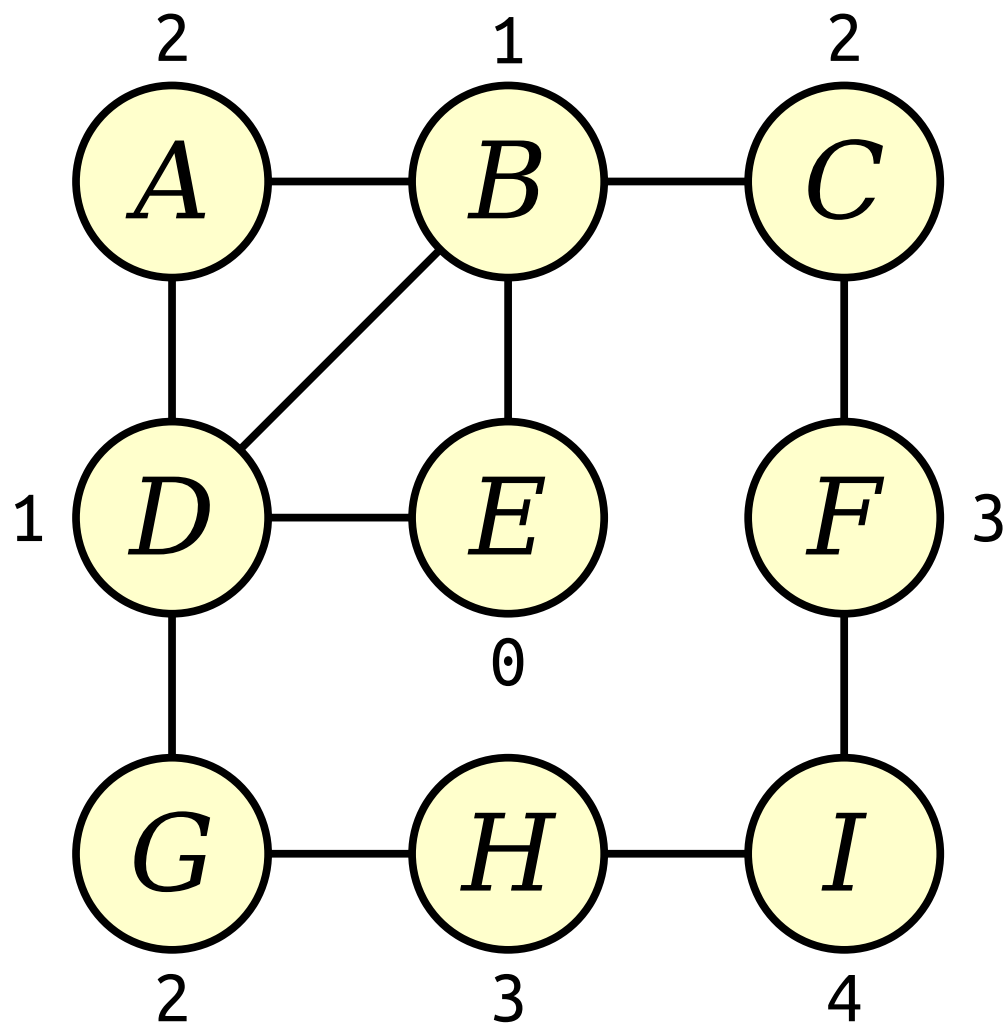


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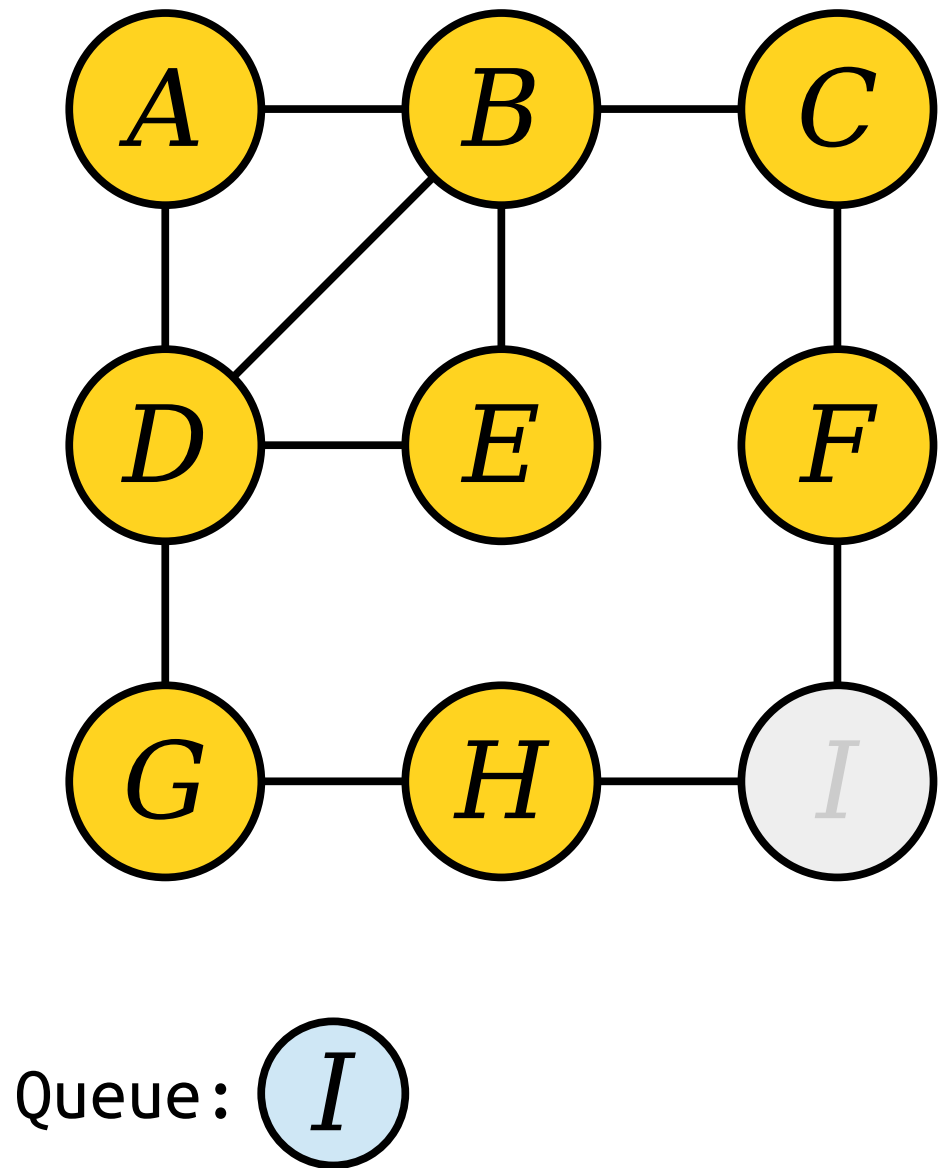


Queue: *I*

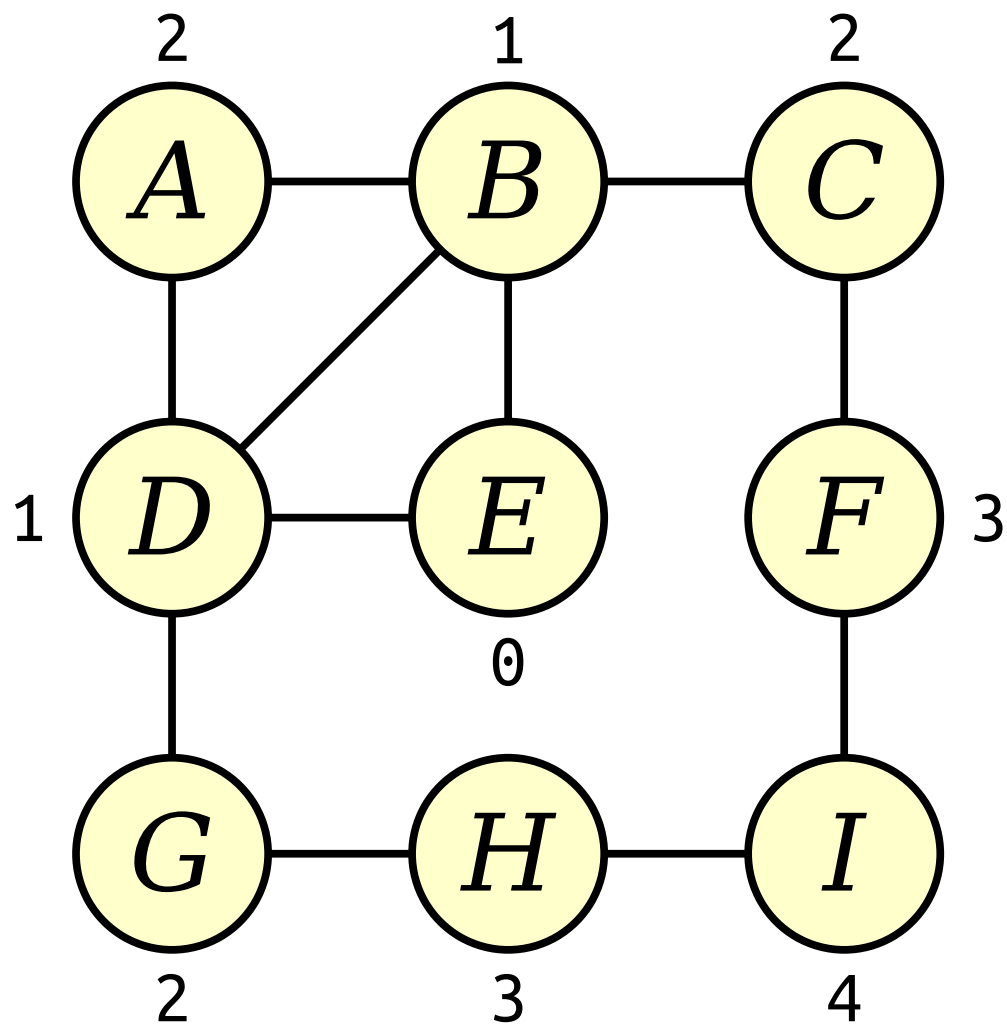
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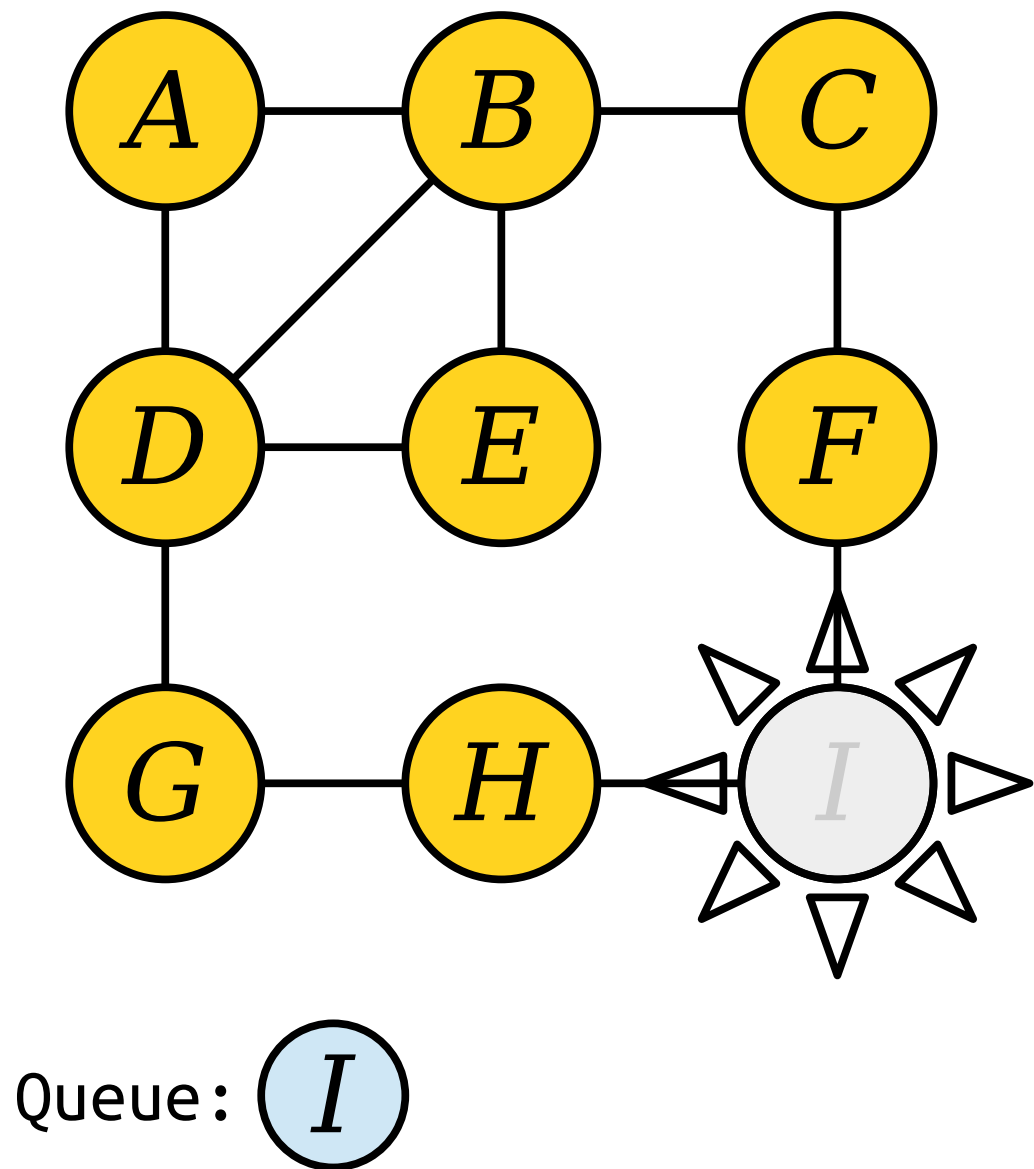
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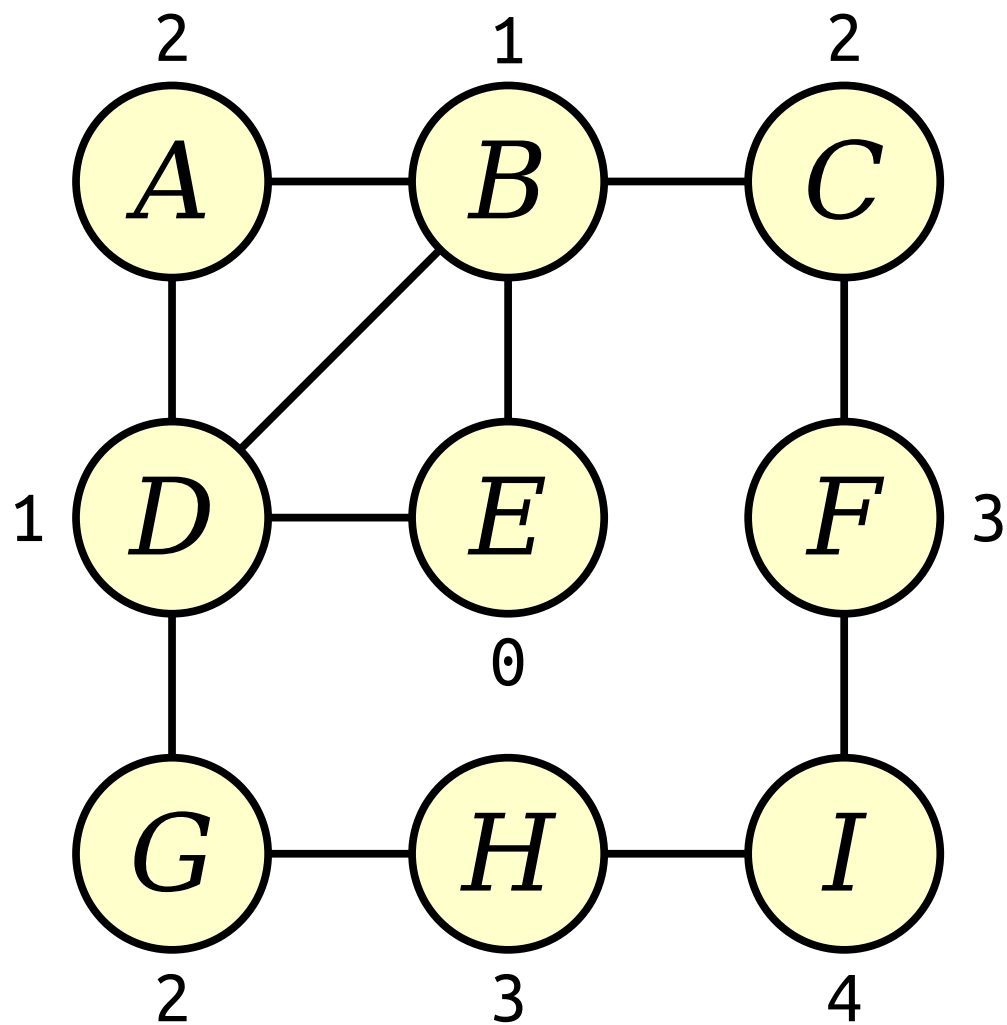
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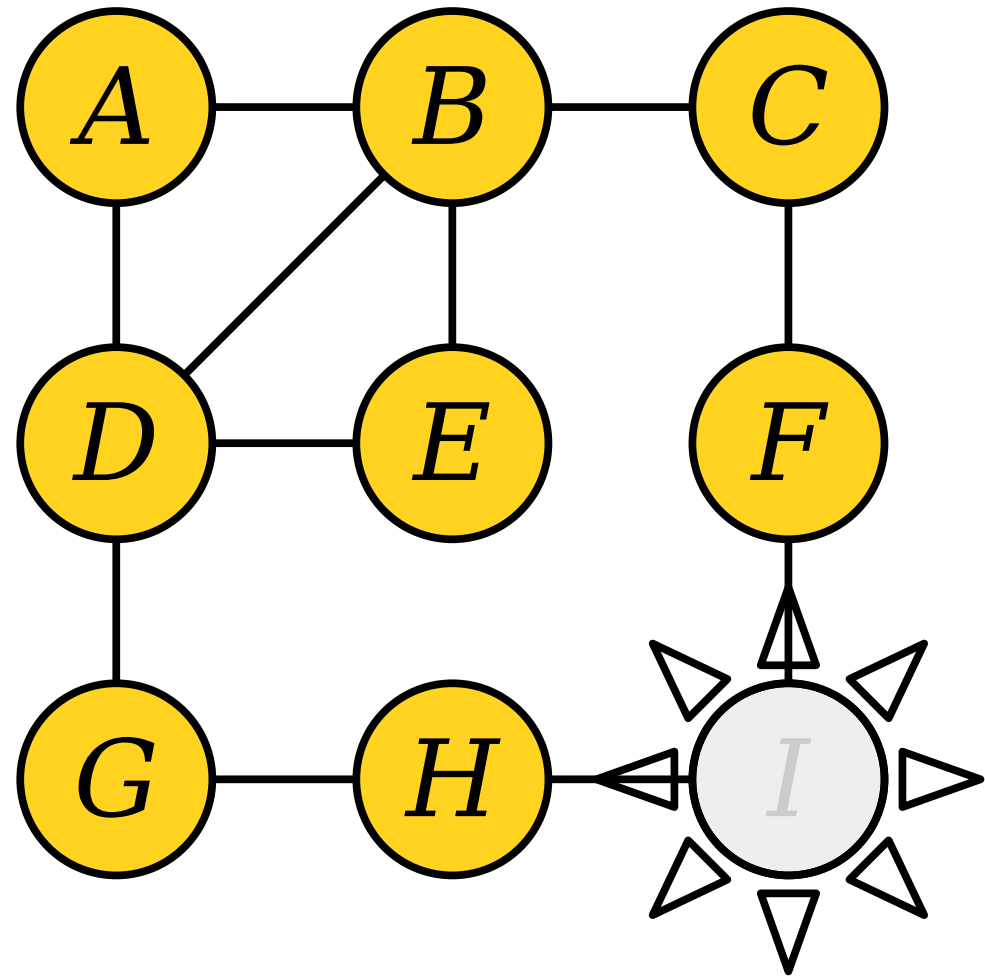
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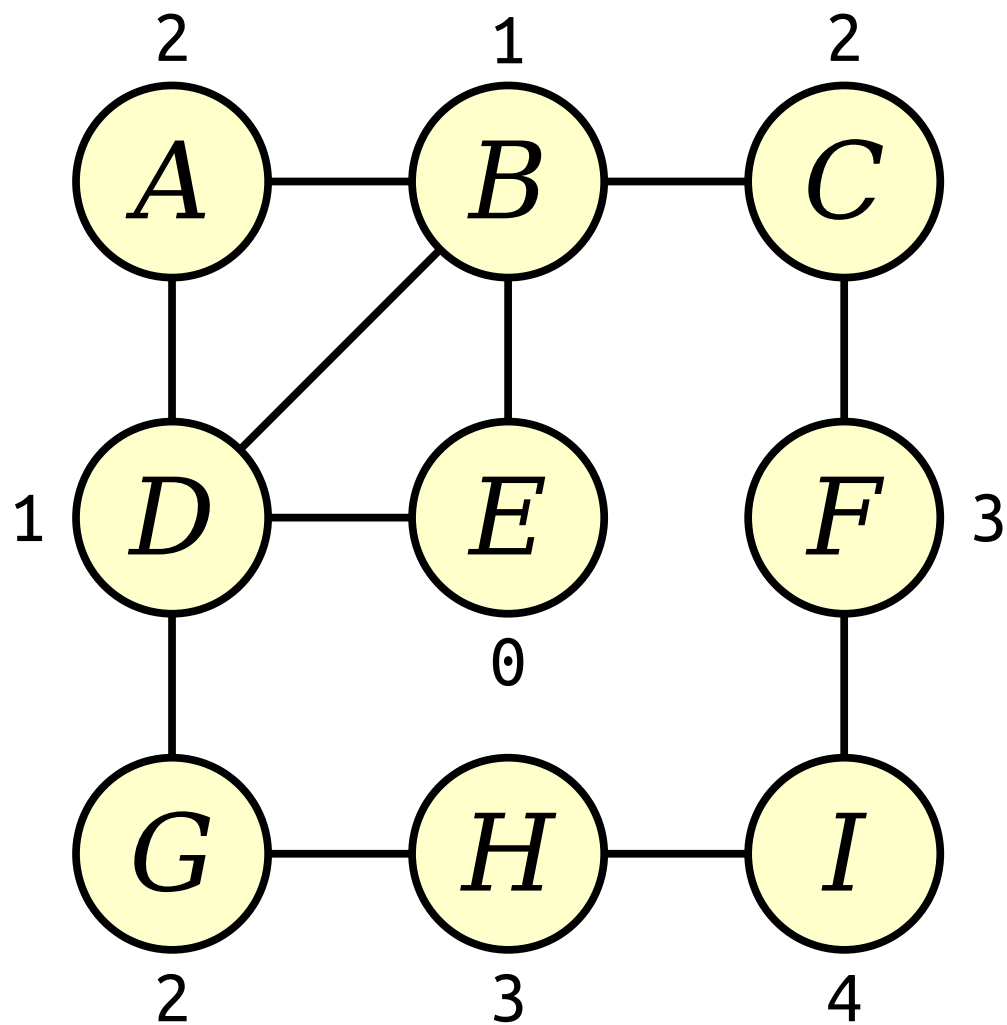


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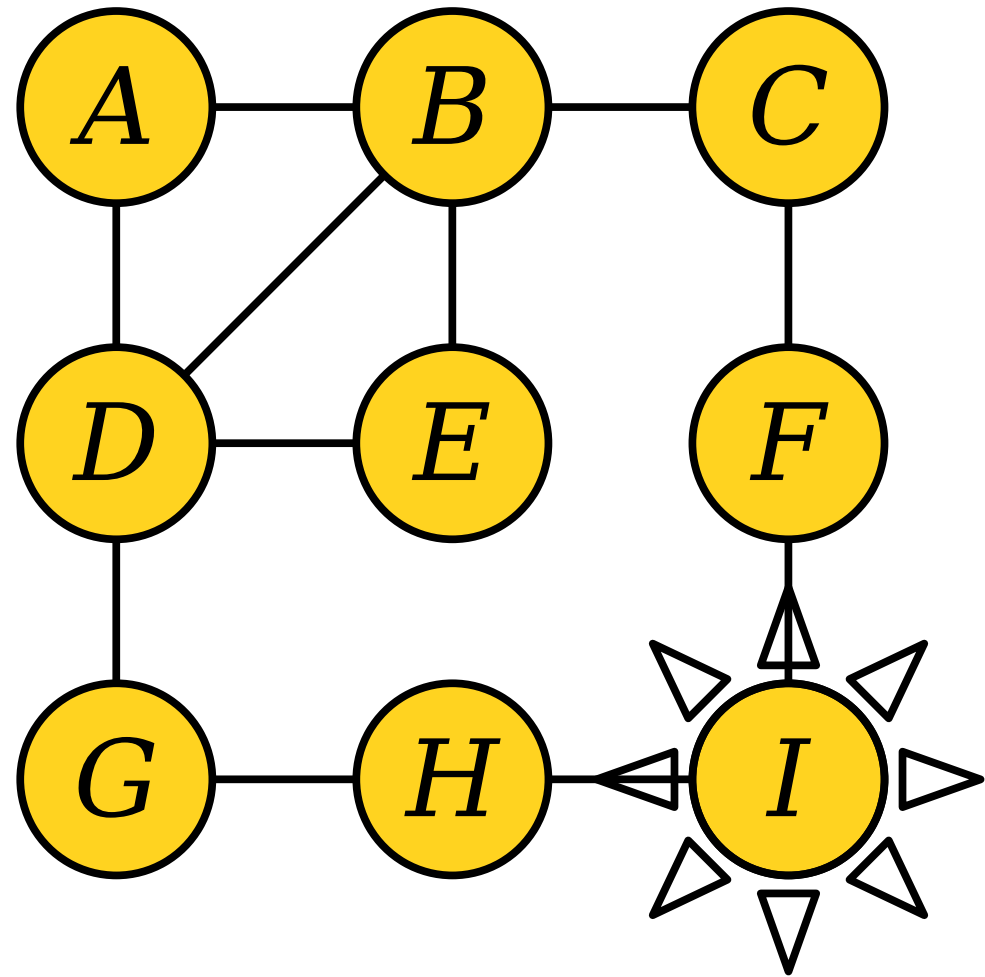


Queue:

Load newly-discovered nodes into a queue.

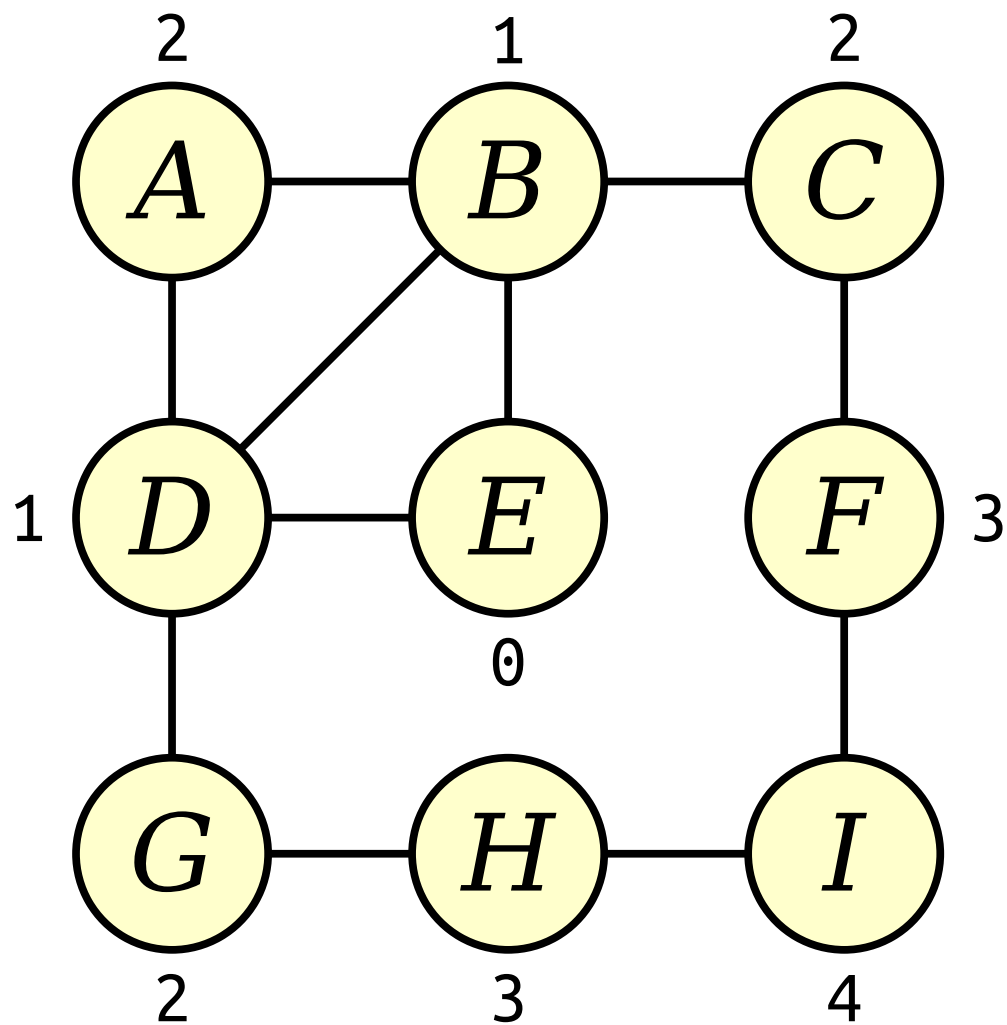


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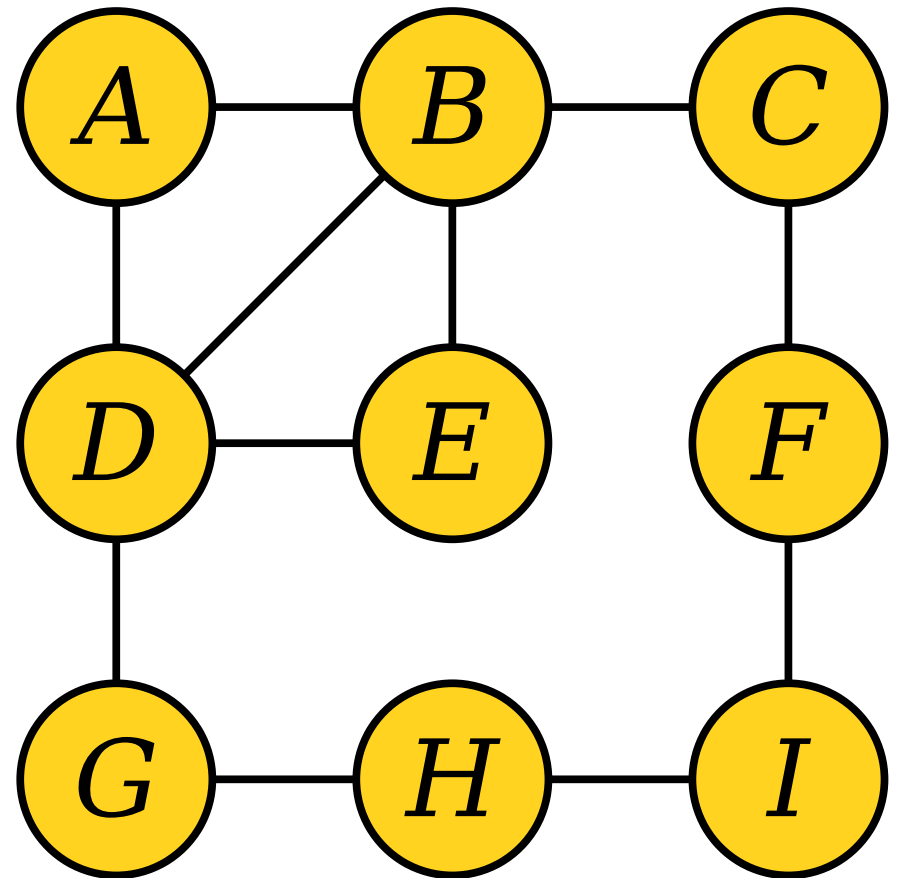


Queue:

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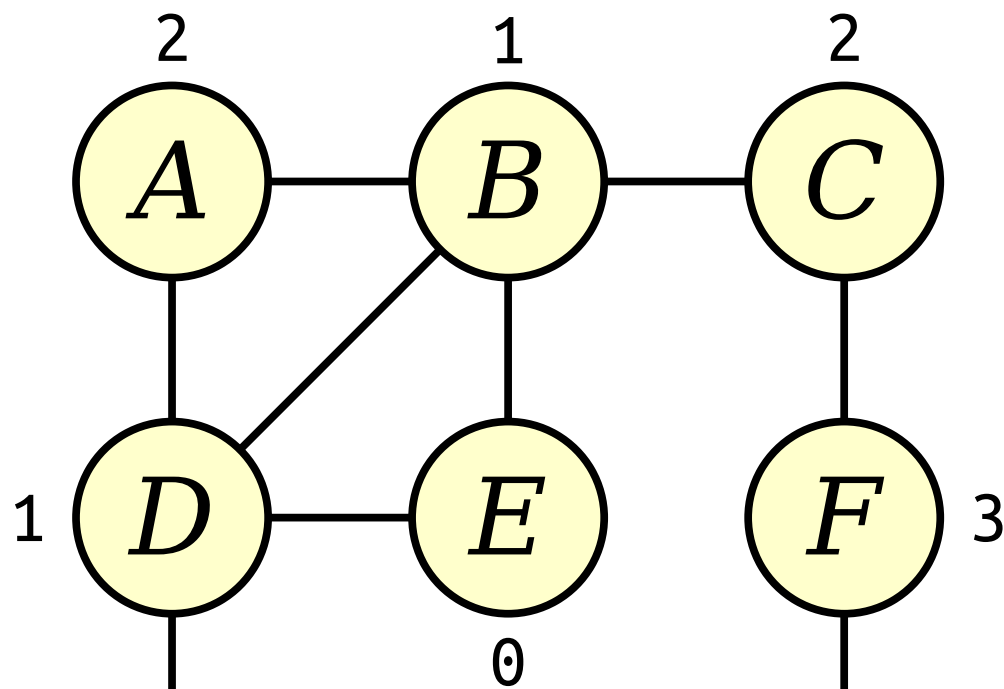


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Queue:

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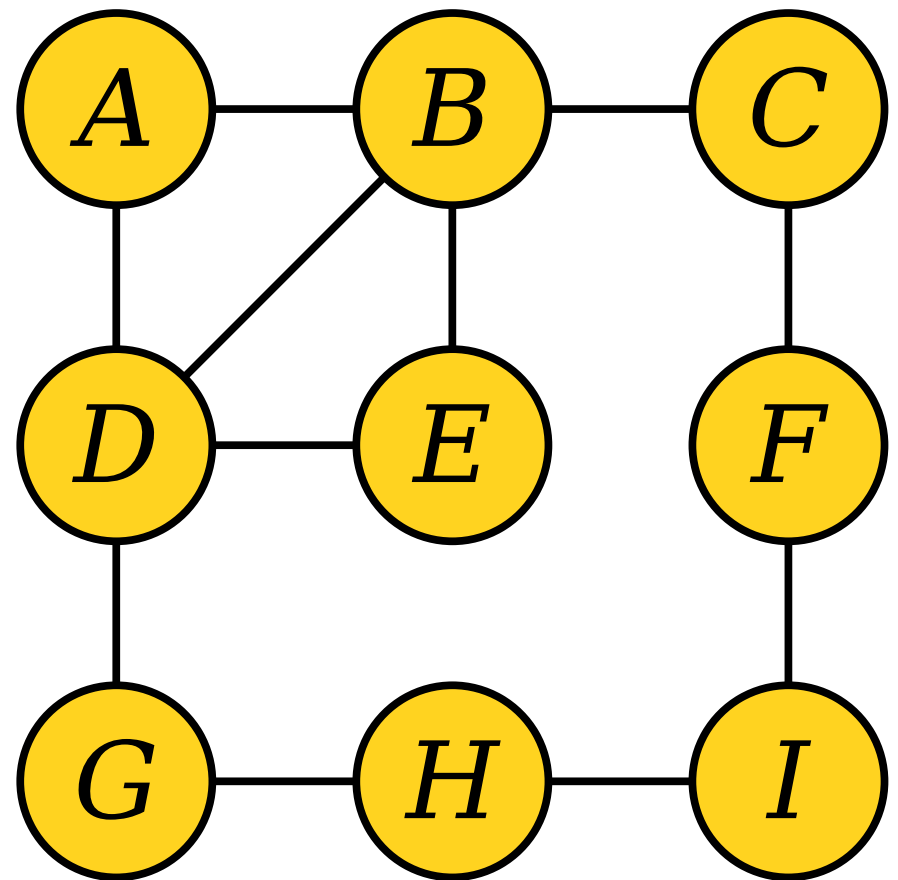


Where have you seen this before?

Answer at

<https://pollev.com/cs106bwin23>

Visit nodes in ascending order of distance from the start node *E*.



Queue:

Load newly-discovered nodes into a queue.

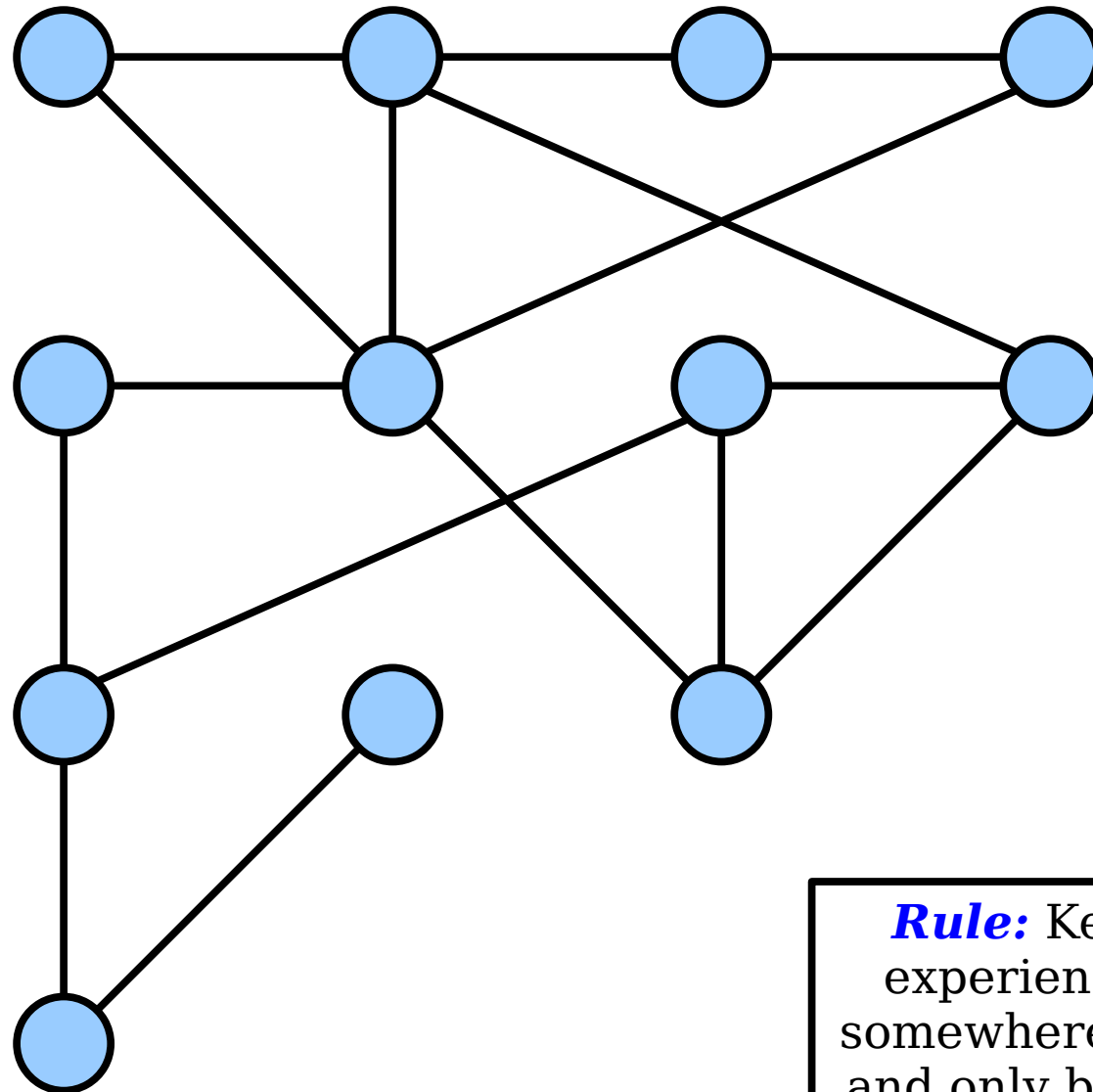
Breadth-First Search

- The Queue-based search strategy we just saw is called ***breadth-first search*** (or just ***BFS*** for short).
- In pseudocode:

```
bfs-from(node v) {  
    make a queue of nodes, initially seeded with v.  
    while the queue isn't empty:  
        dequeue a node curr.  
        process the node curr.  
        for each node adjacent to curr:  
            if that node has never been enqueued:  
                enqueue that node.  
}
```

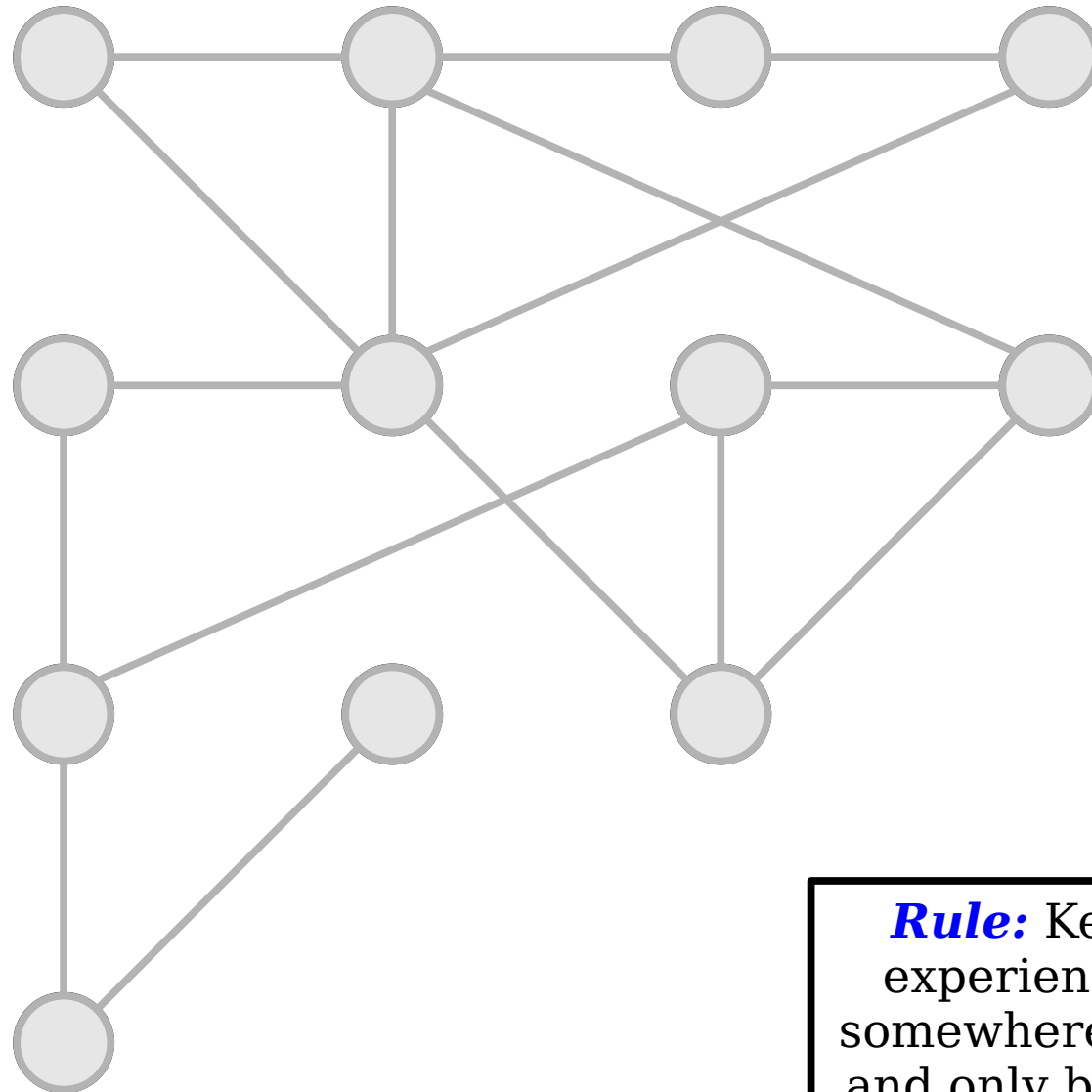

Depth-First Search

Depth-First Search



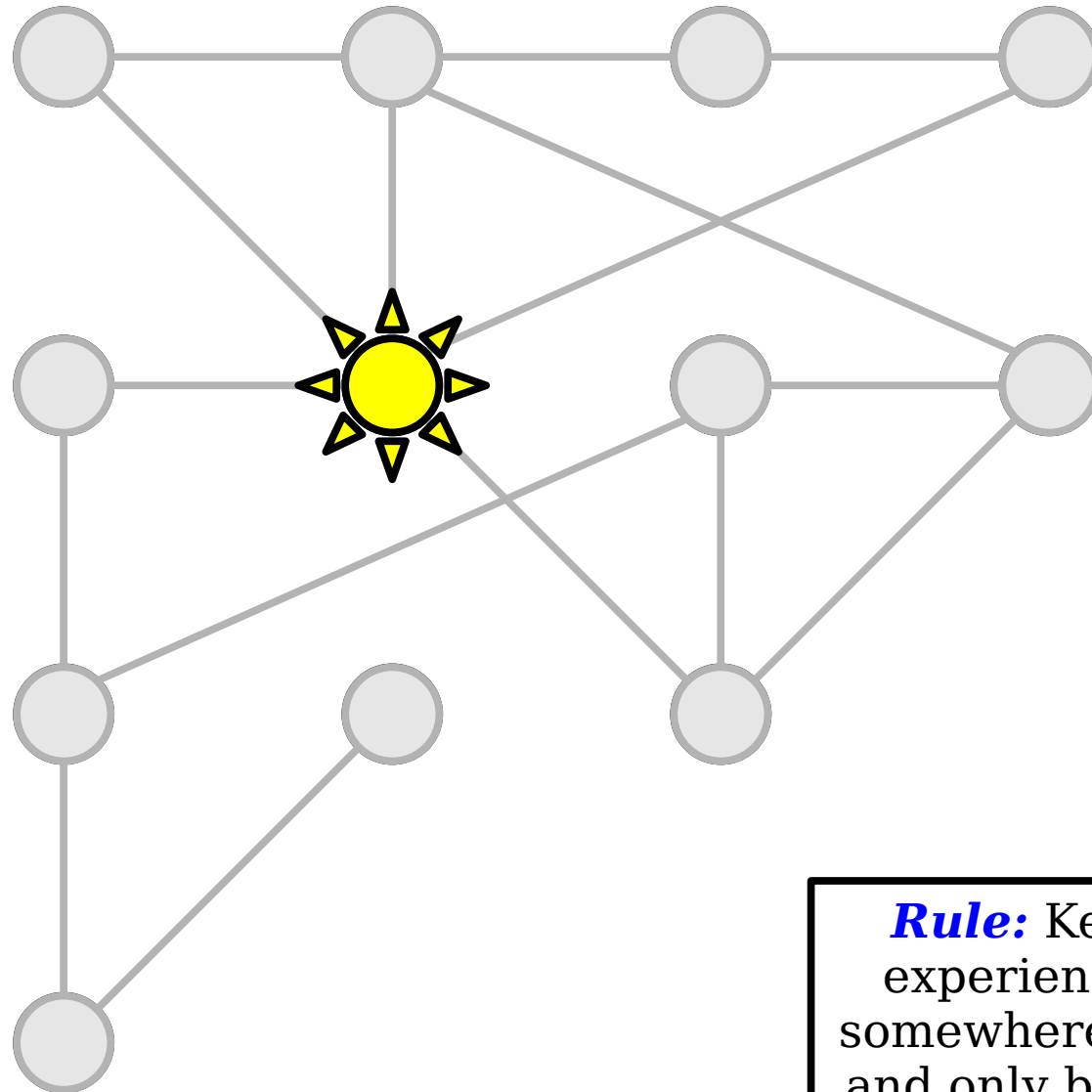
Rule: Keep trying new experiences! Always go somewhere new if you can, and only back up if there's nothing new to see.

Depth-First Search



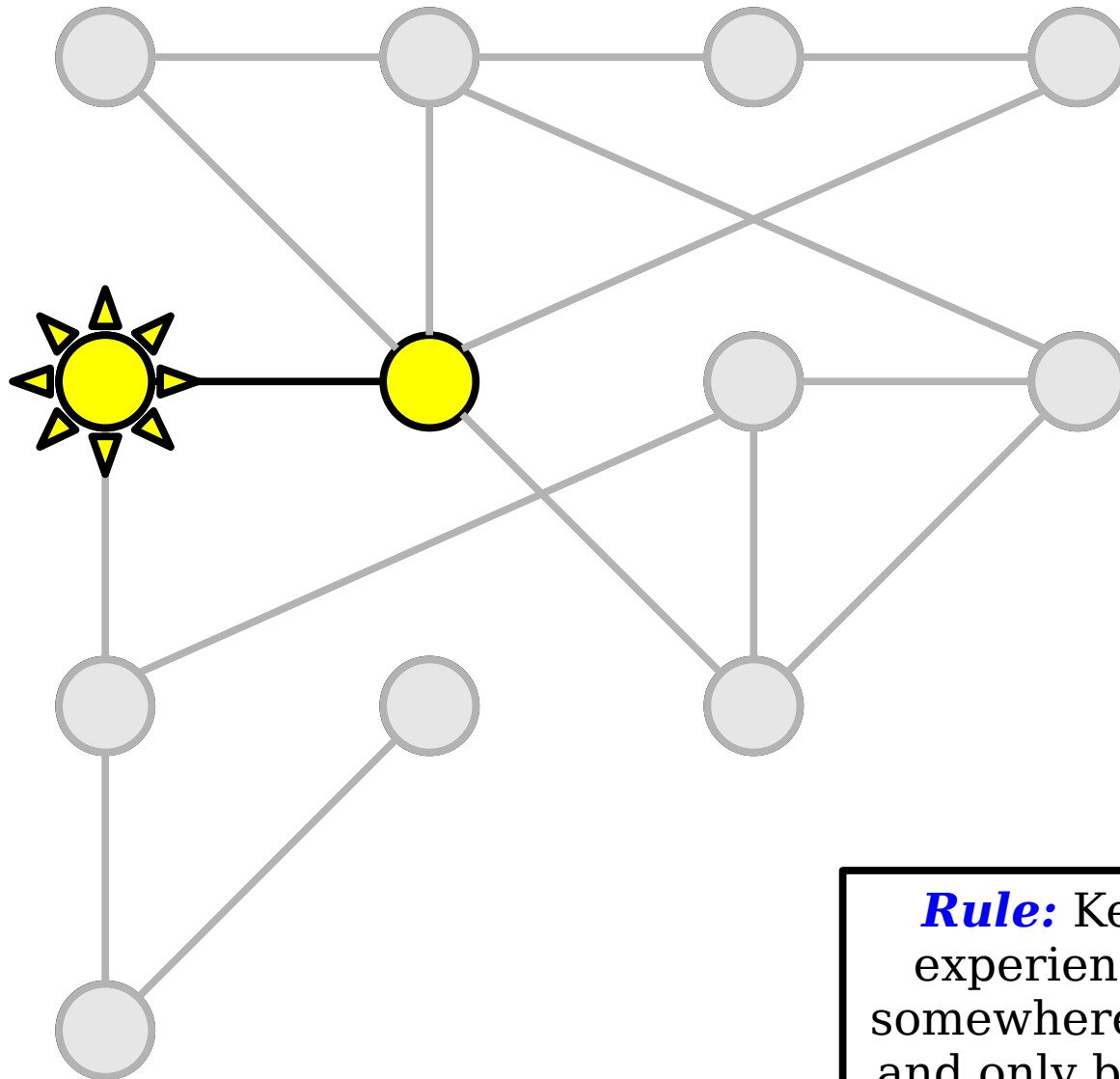
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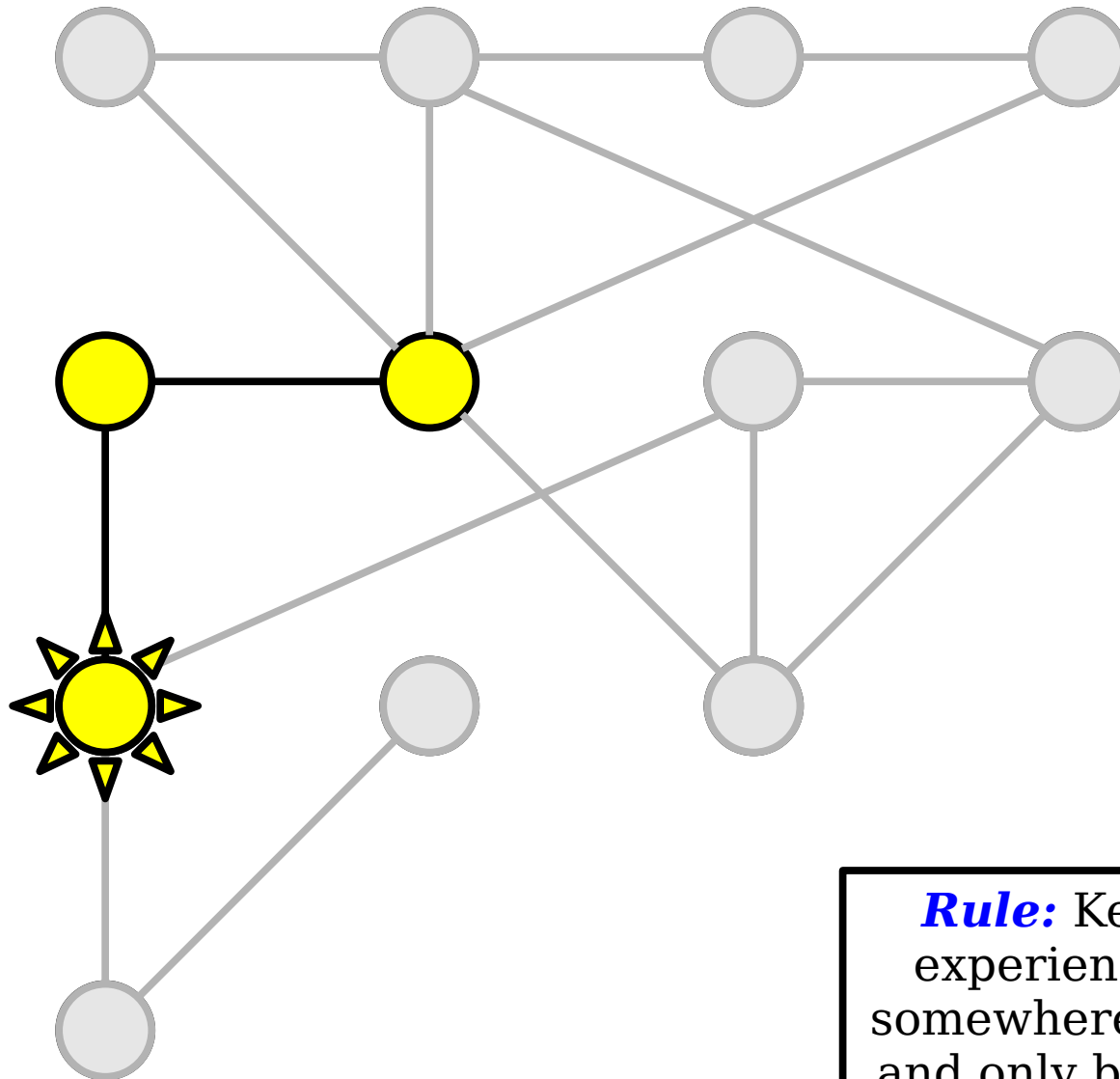
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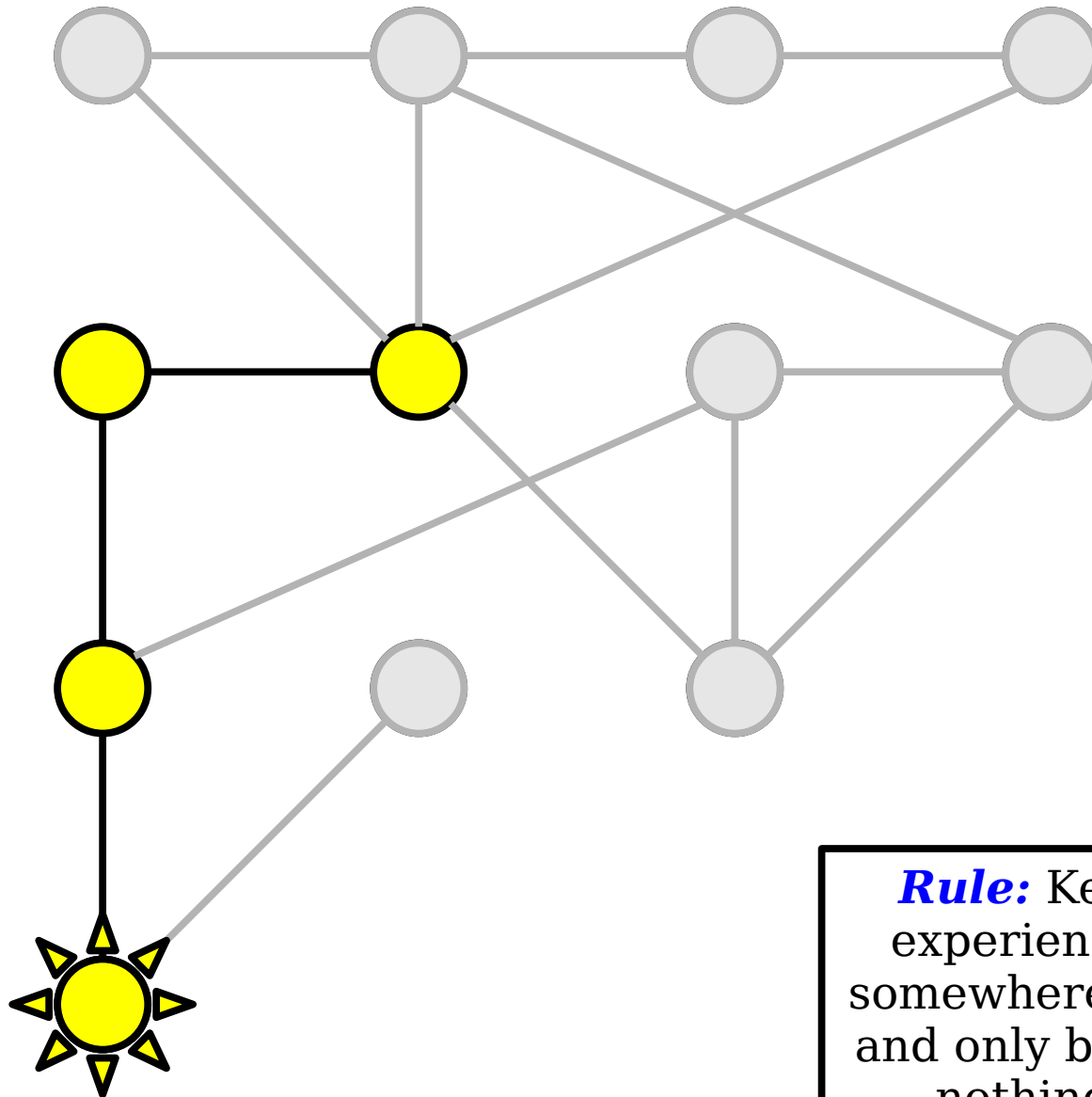
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Depth-First Search



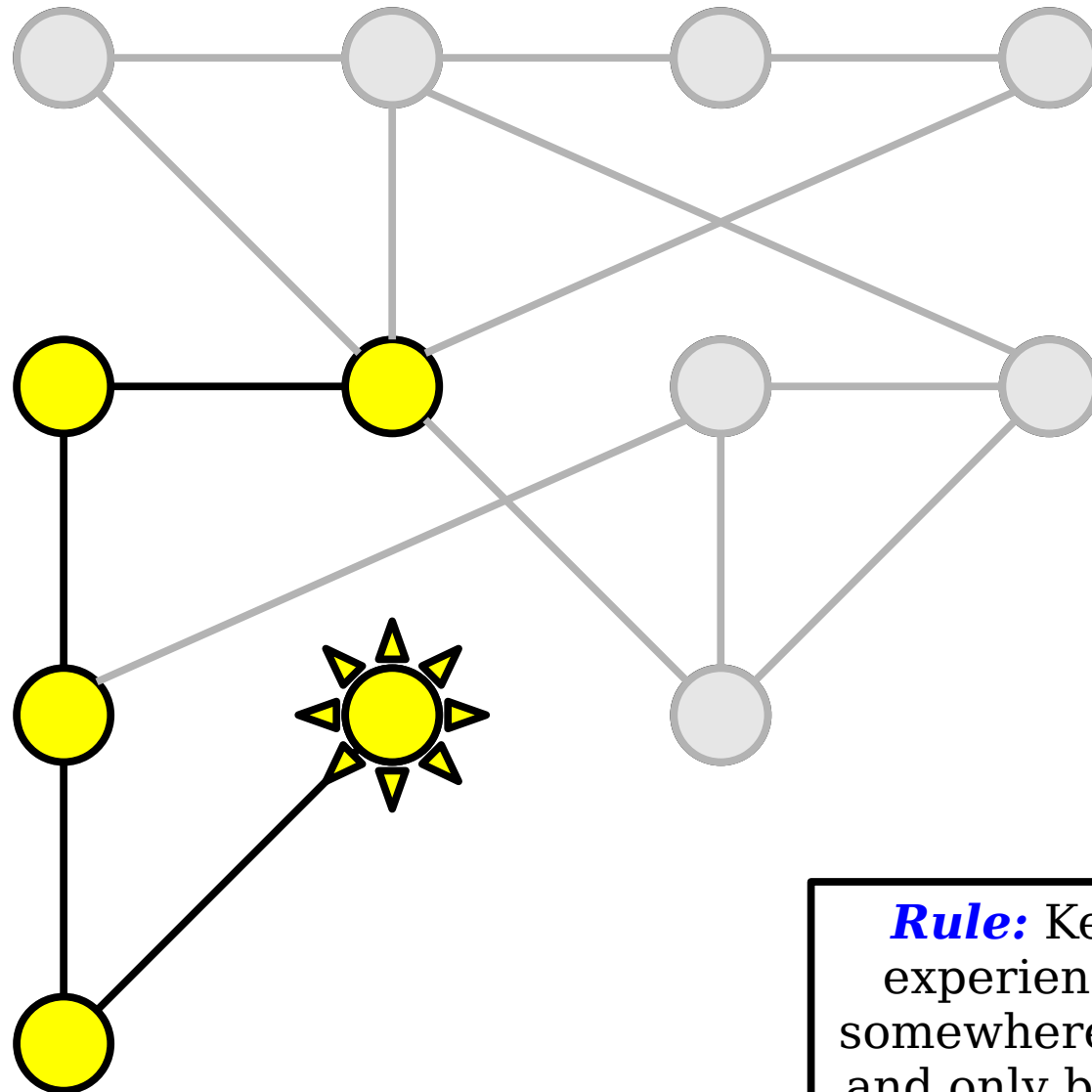
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Depth-First Search



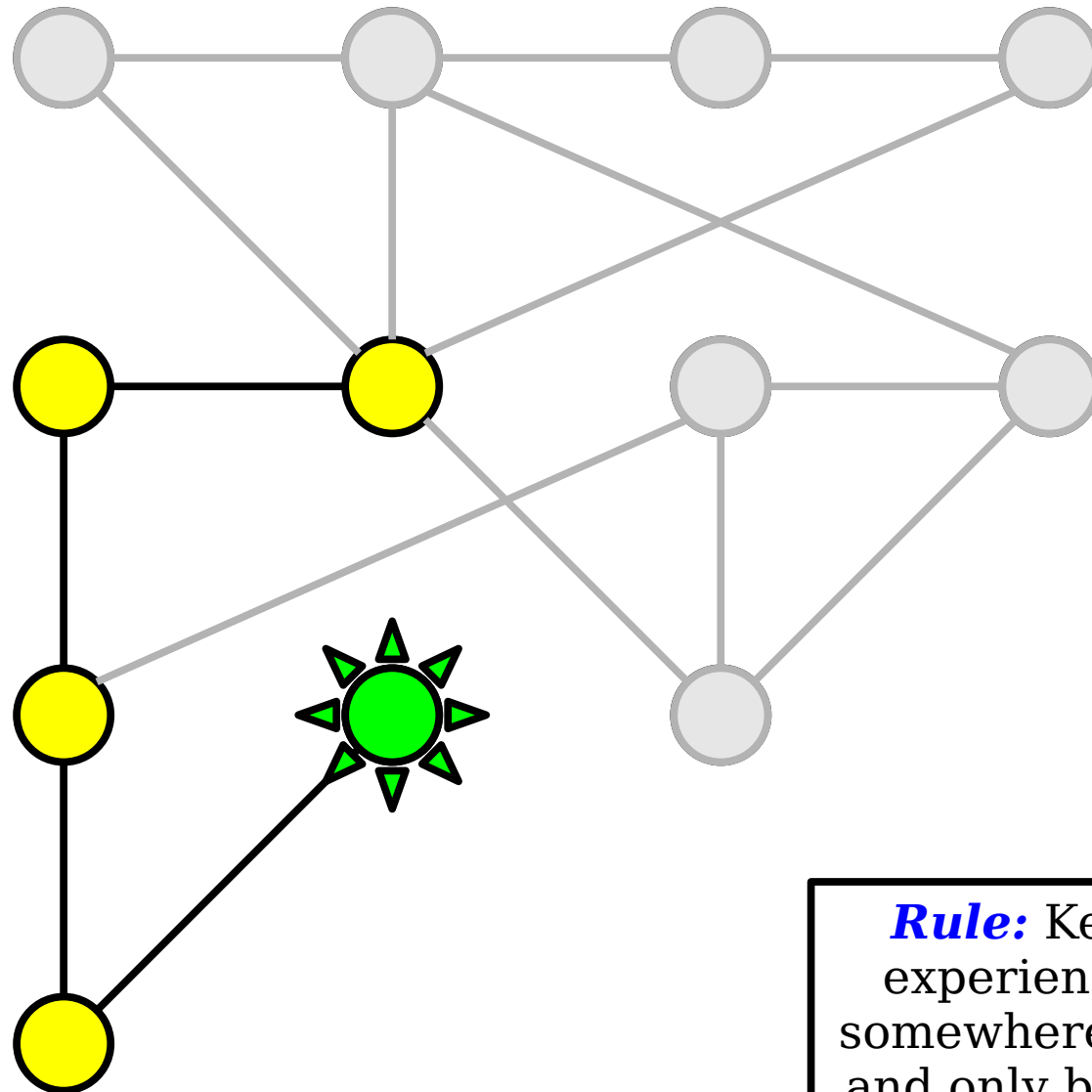
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Depth-First Search



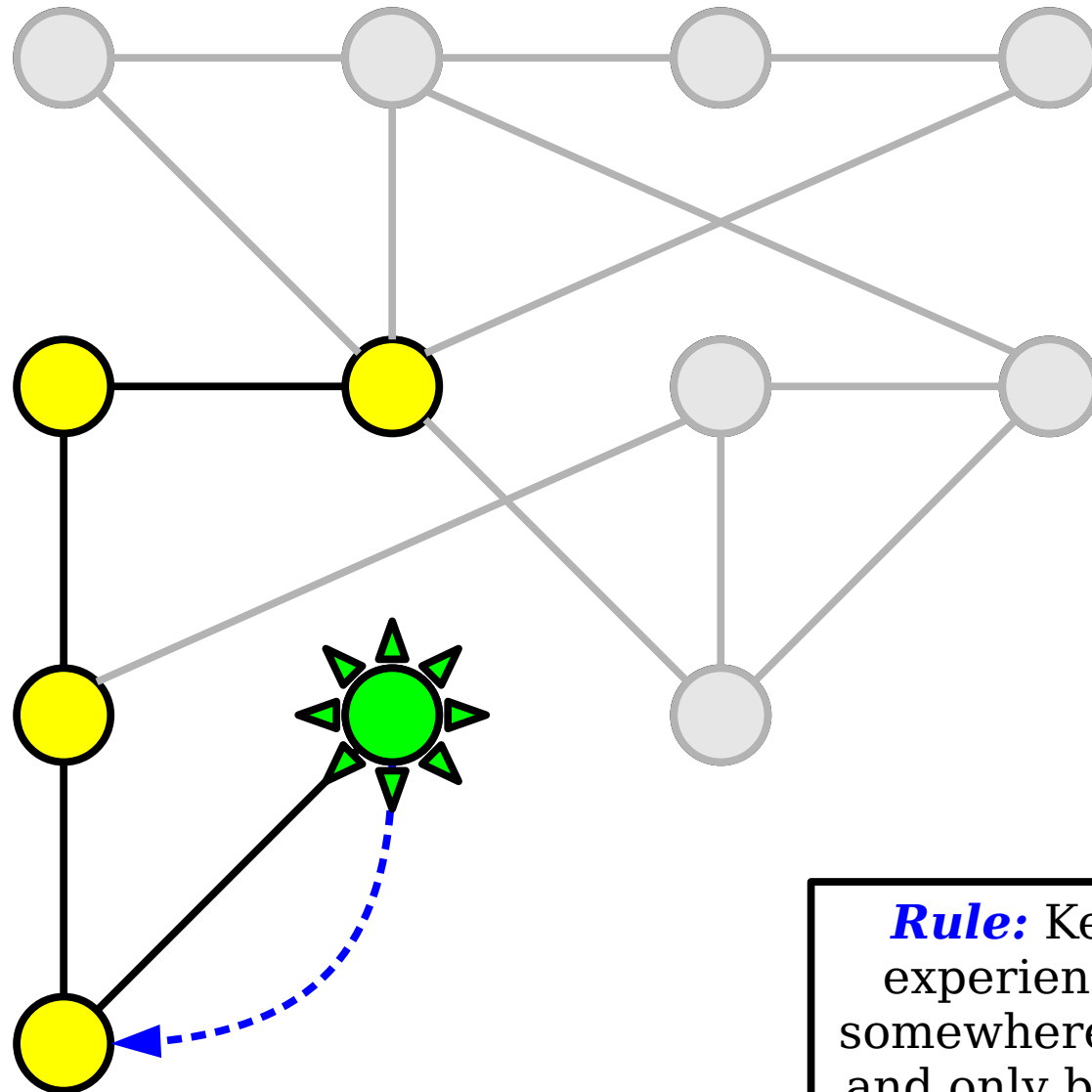
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Depth-First Search



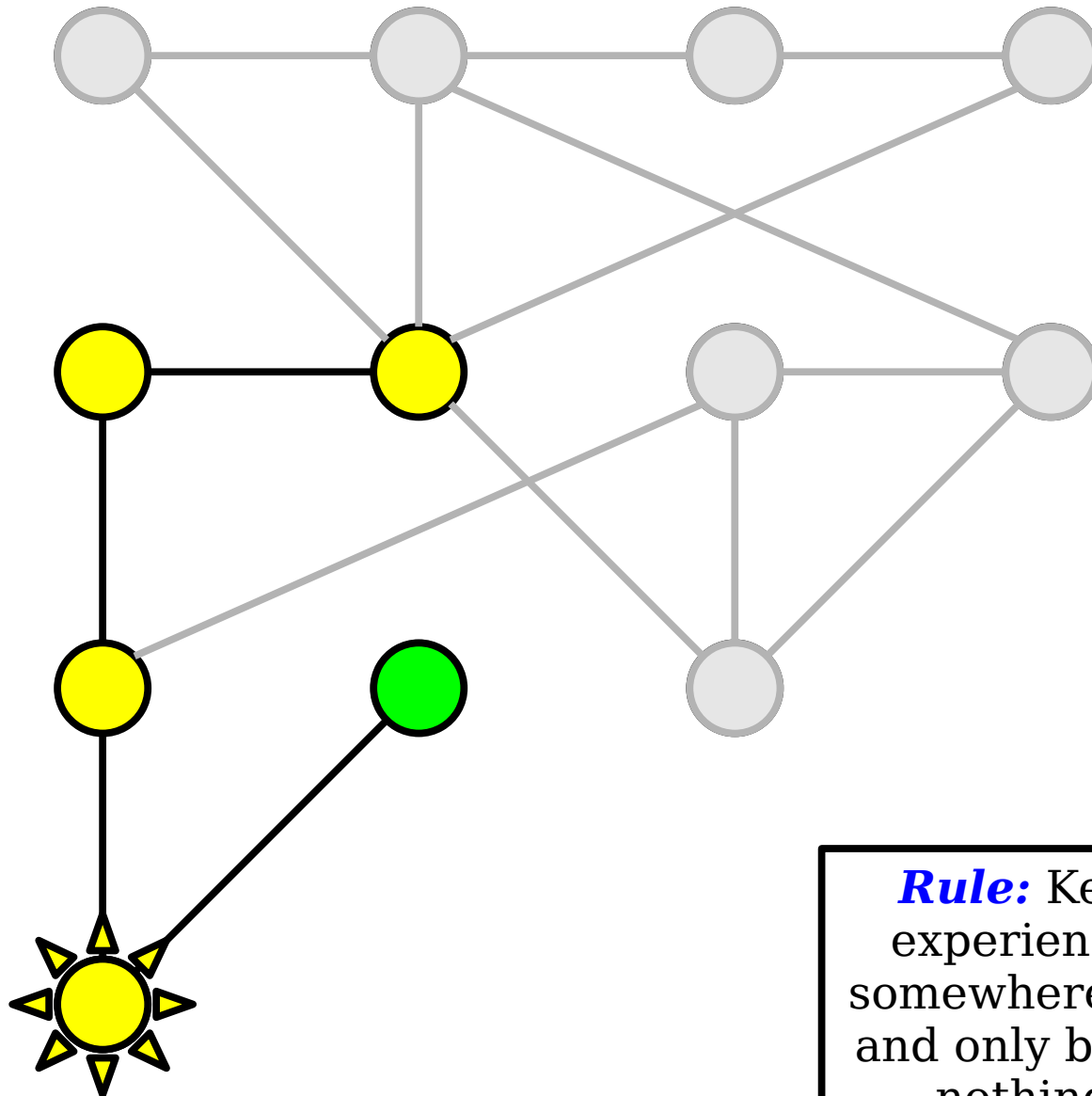
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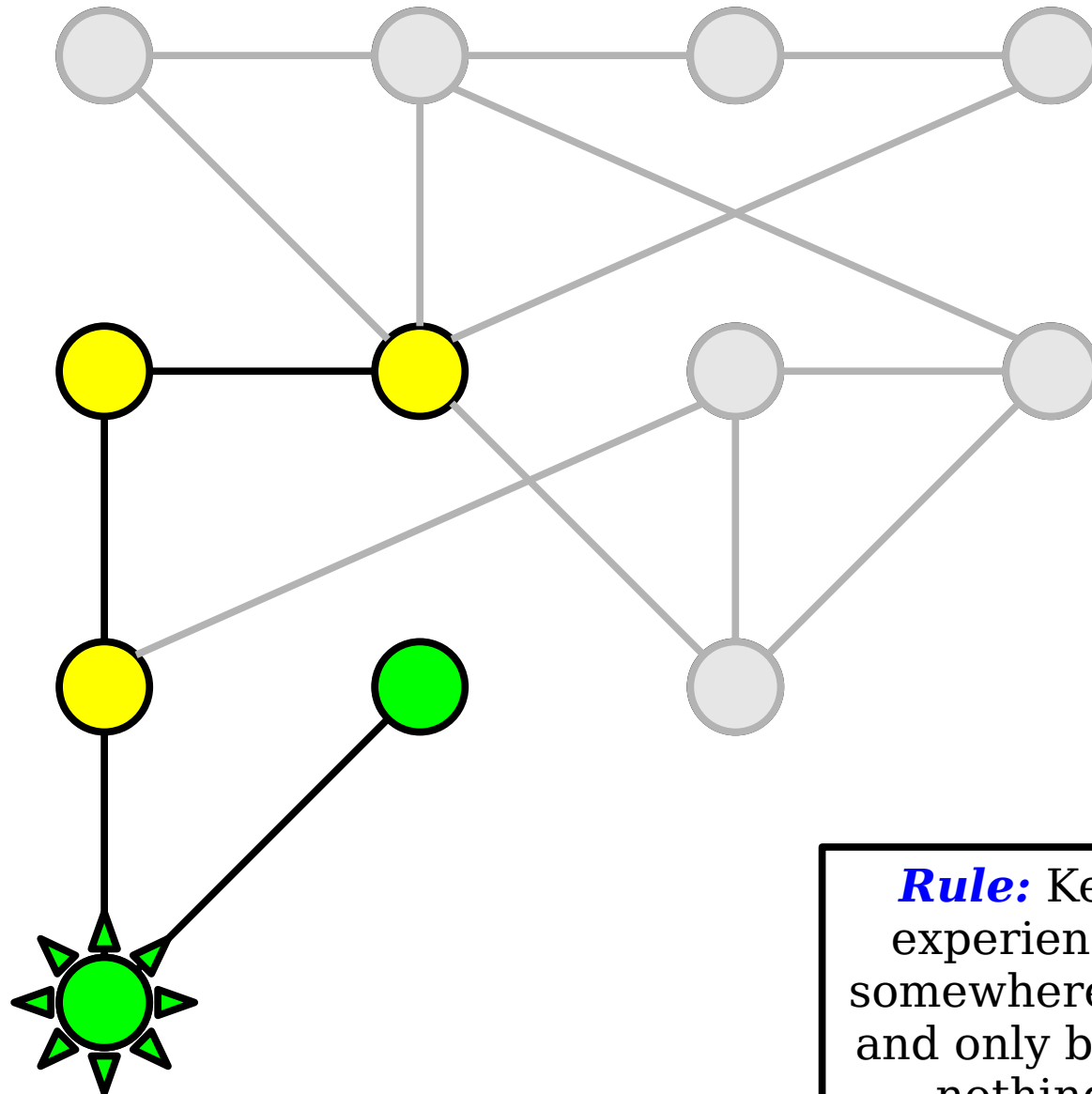
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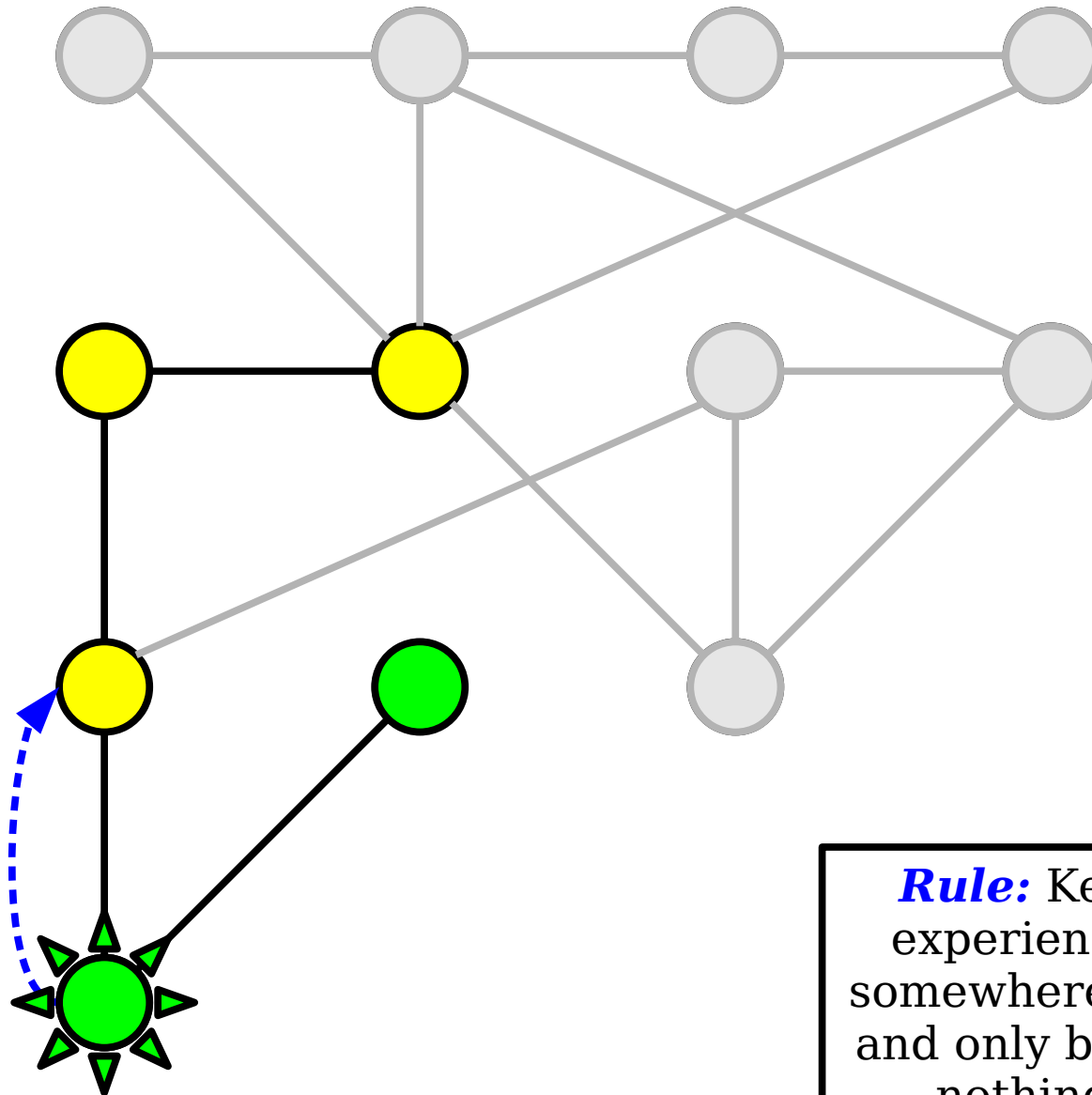
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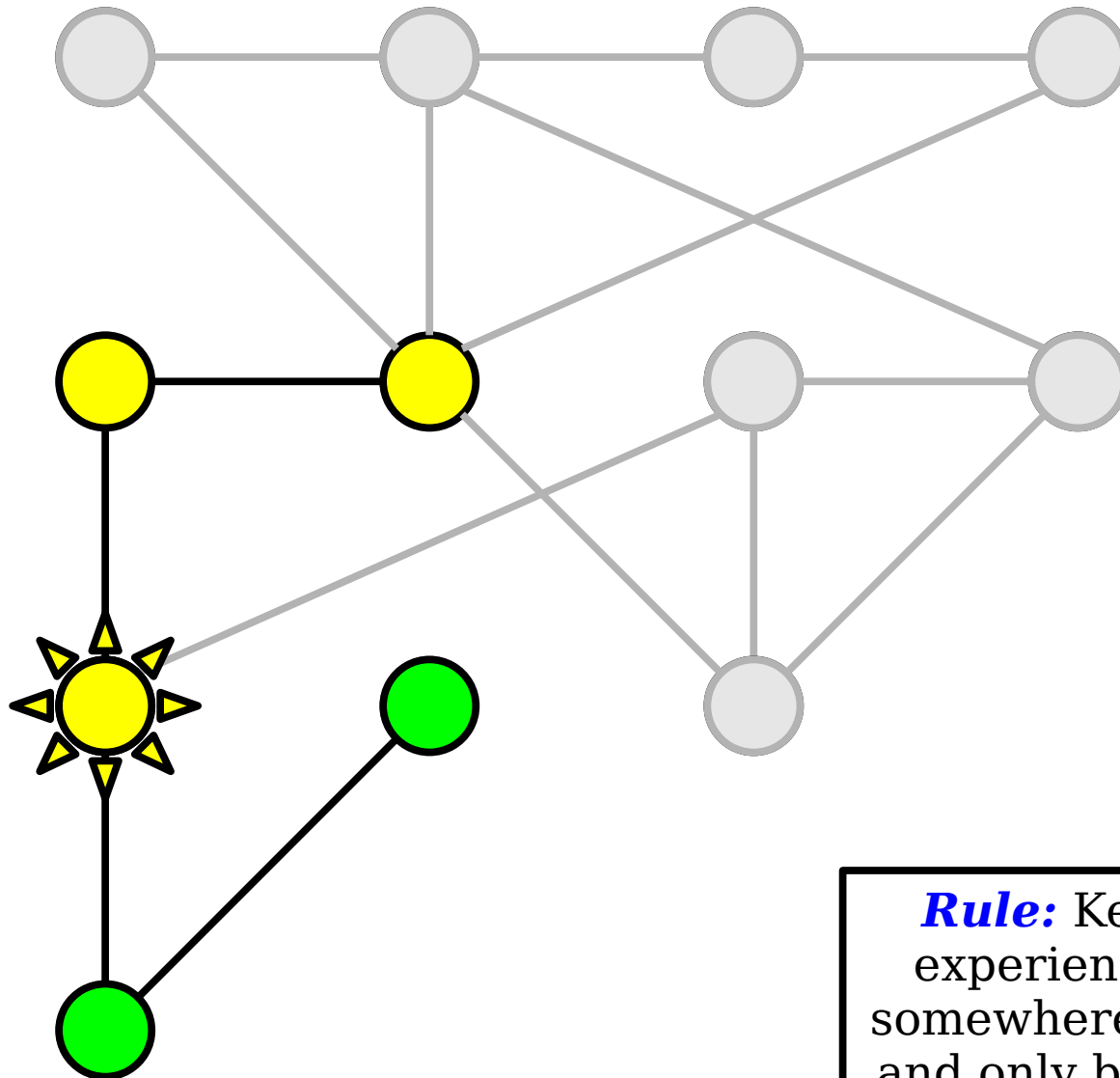
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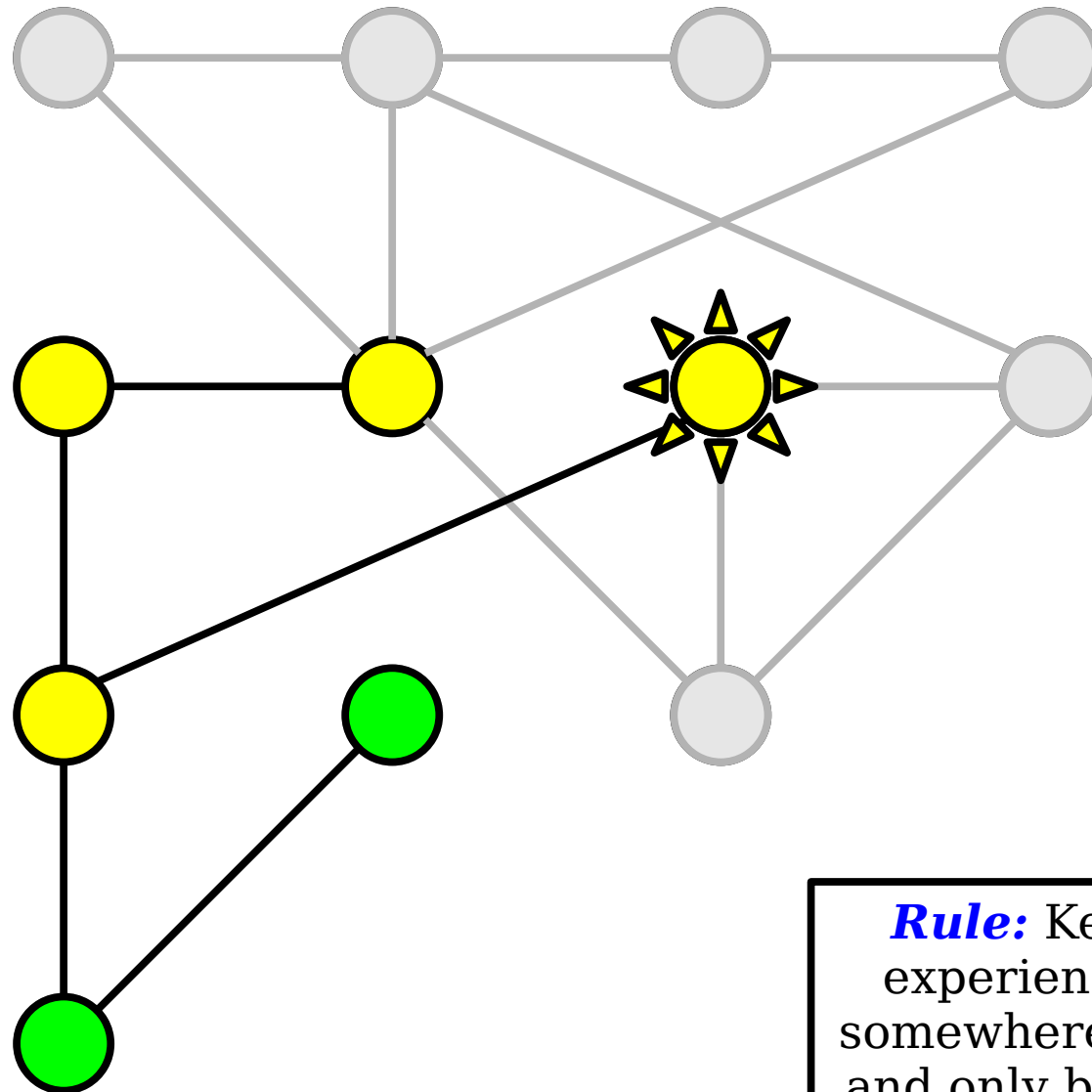
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Depth-First Search



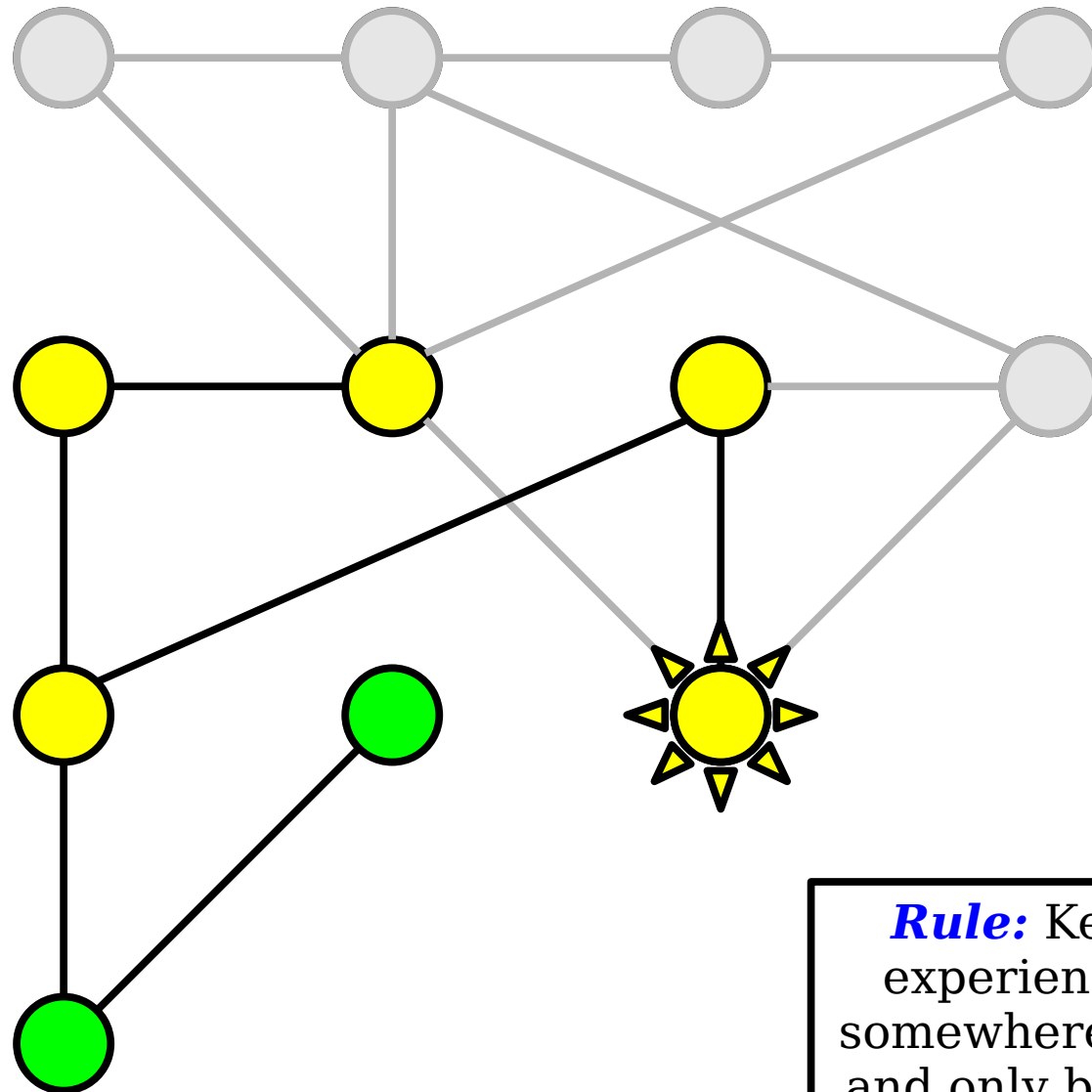
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Depth-First Search



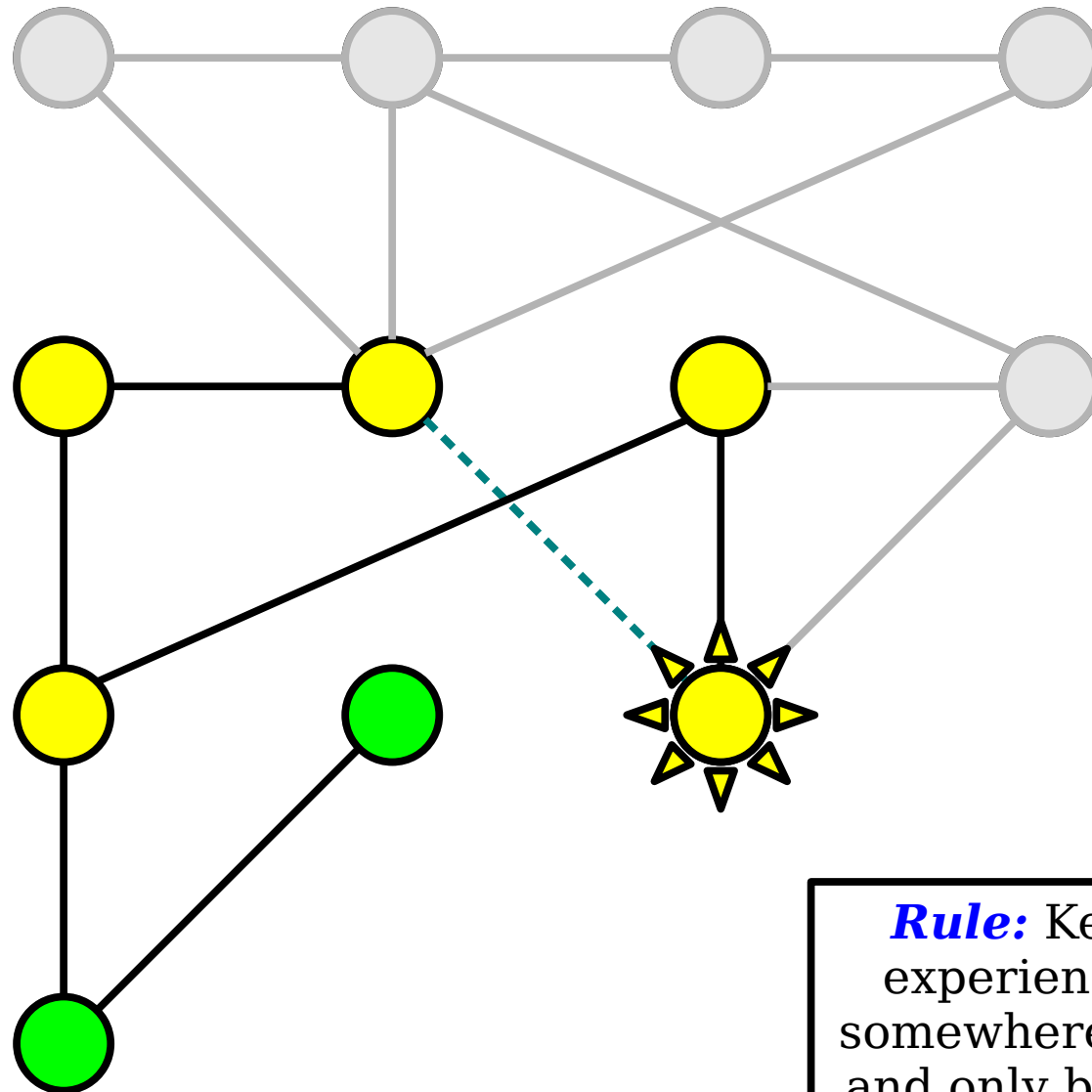
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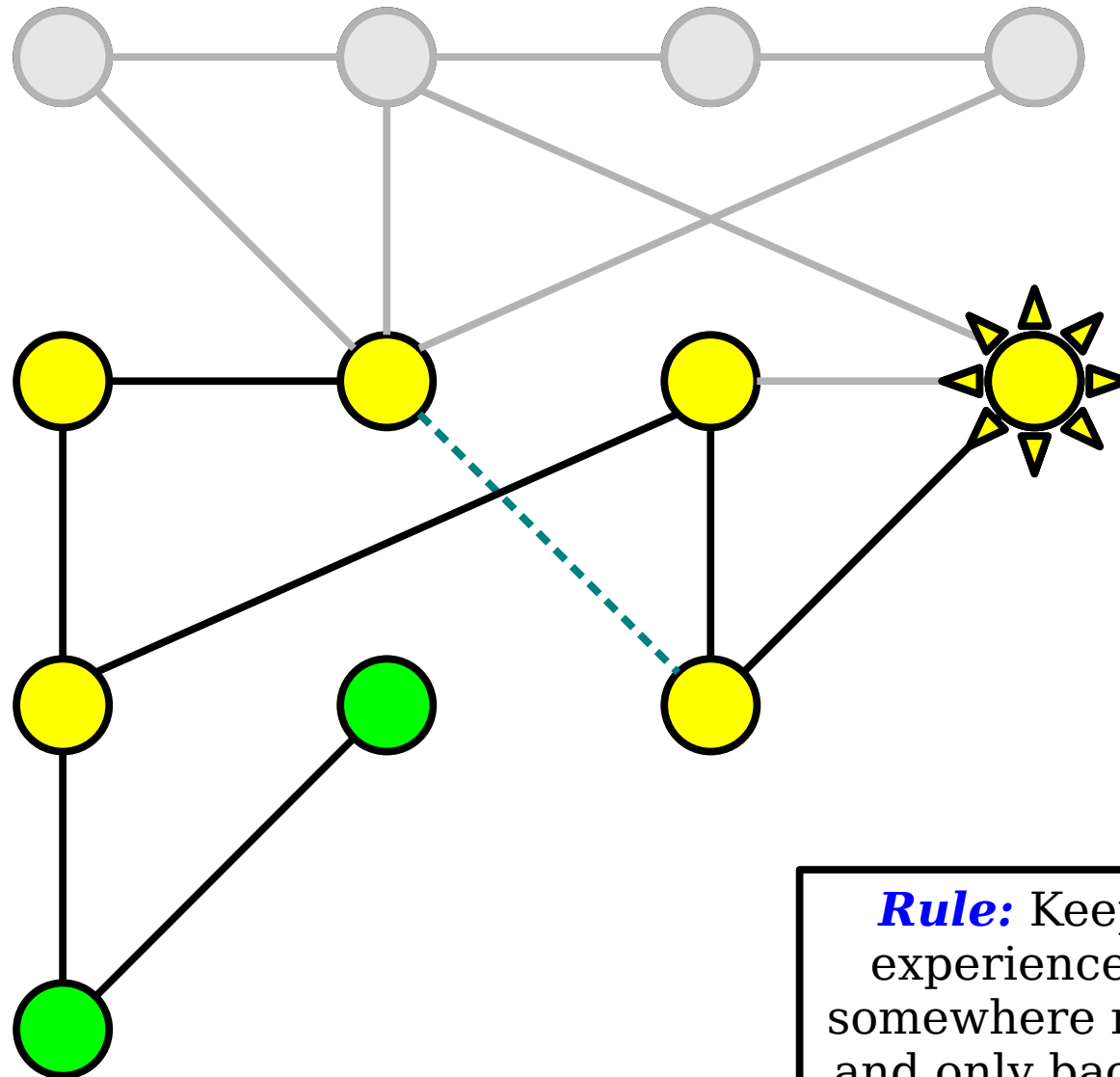
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Depth-First Search



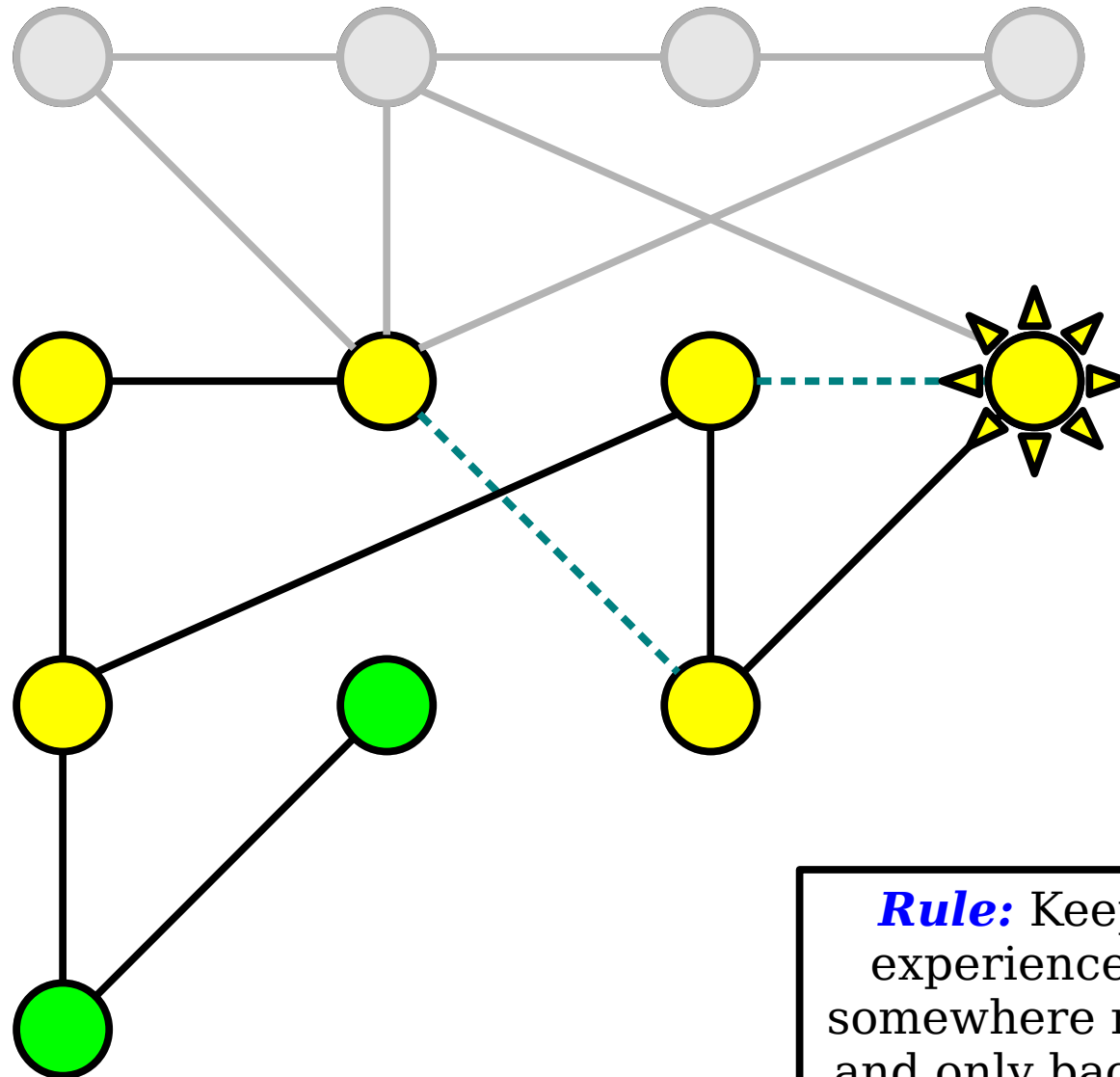
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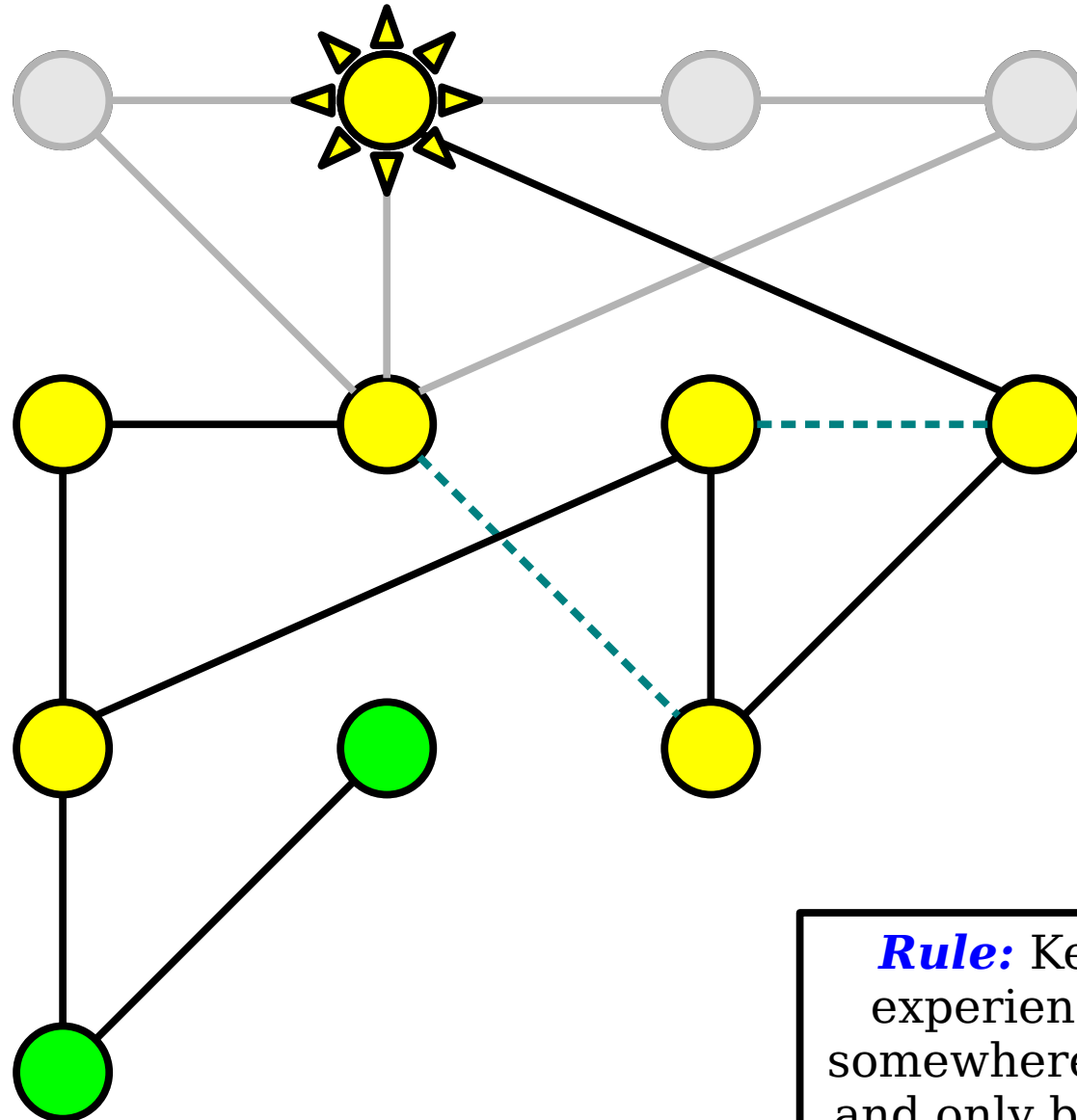
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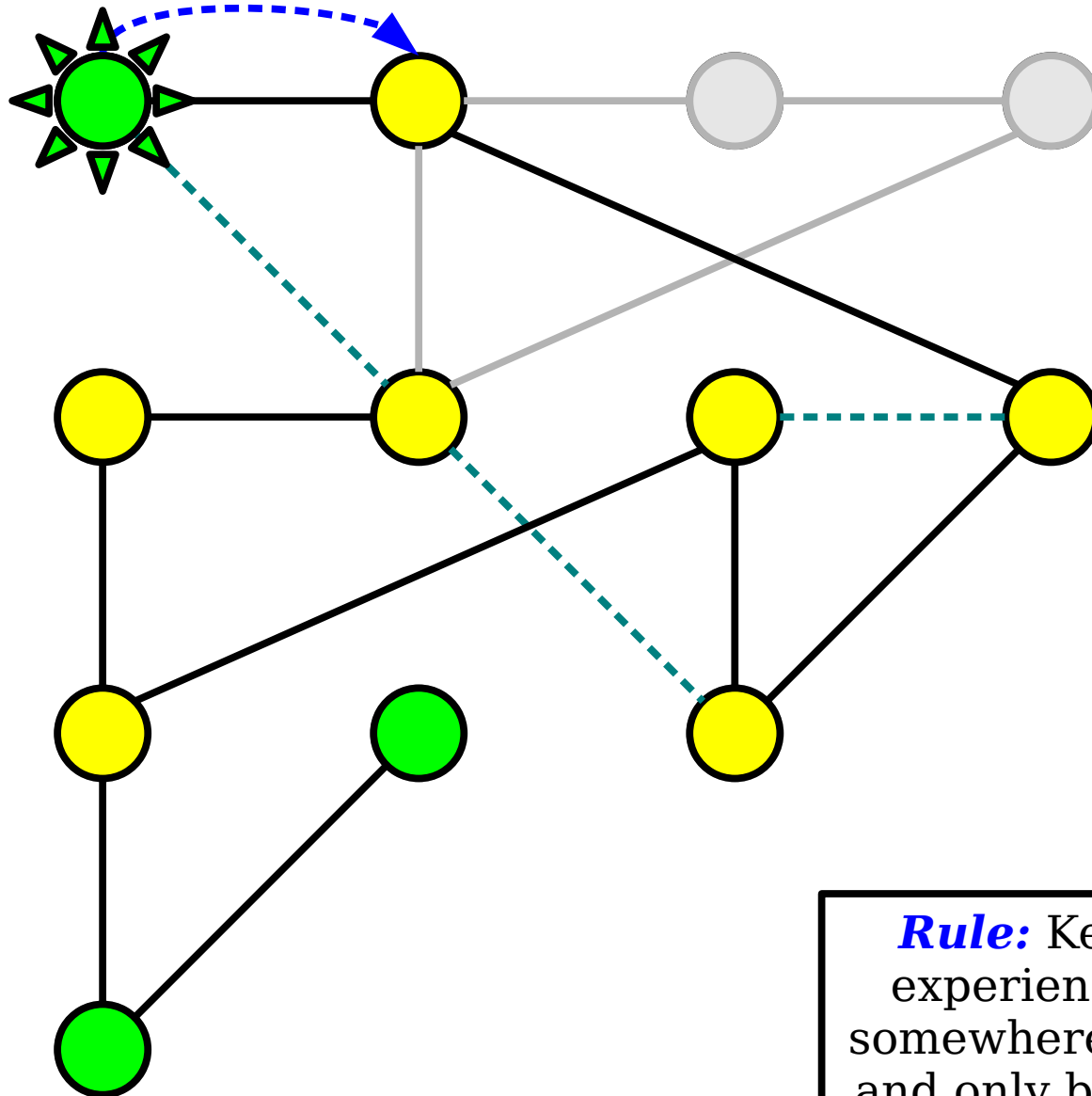
[illegible]

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Rule: Keep the experience somewhere and only have it once

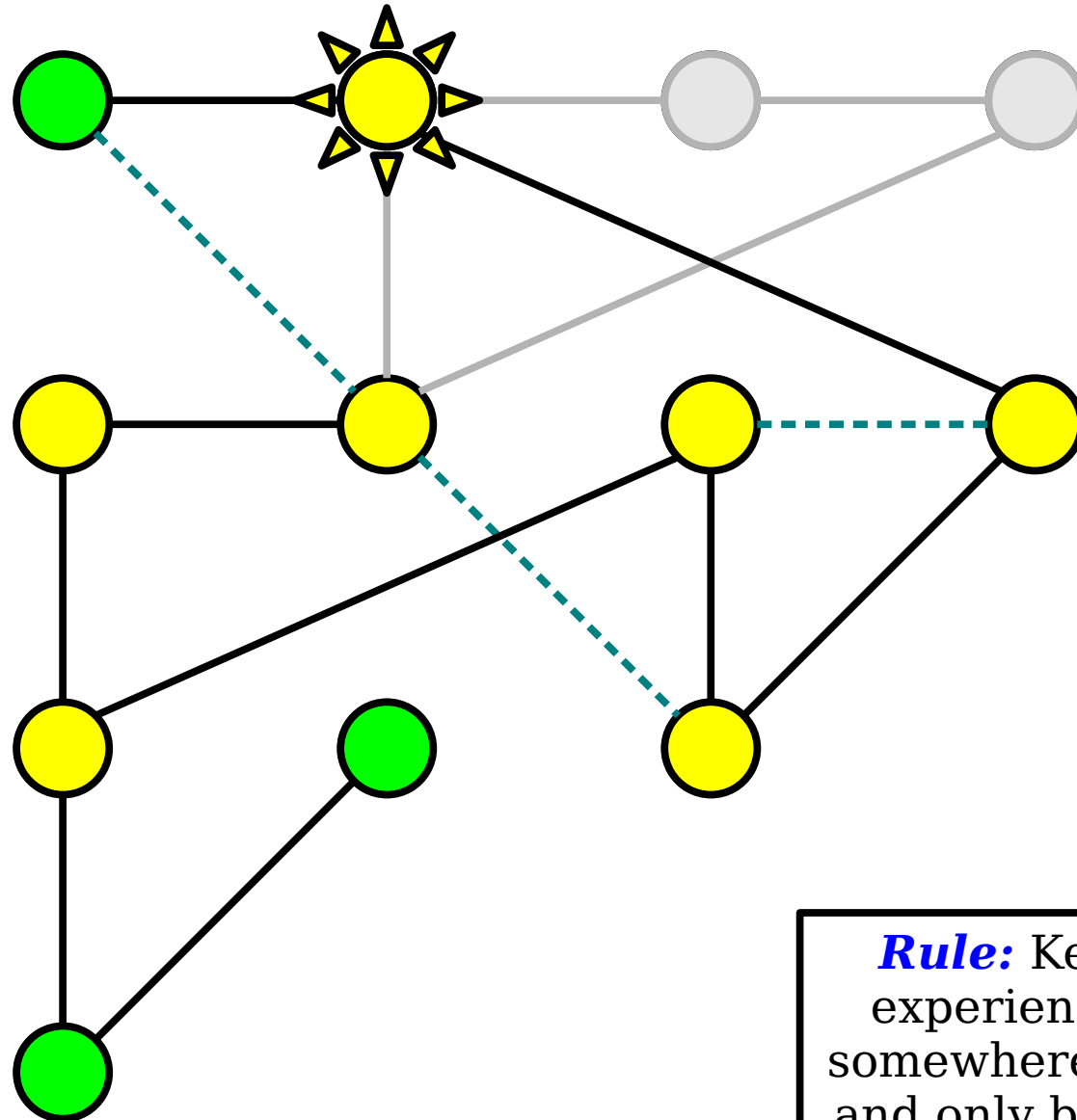
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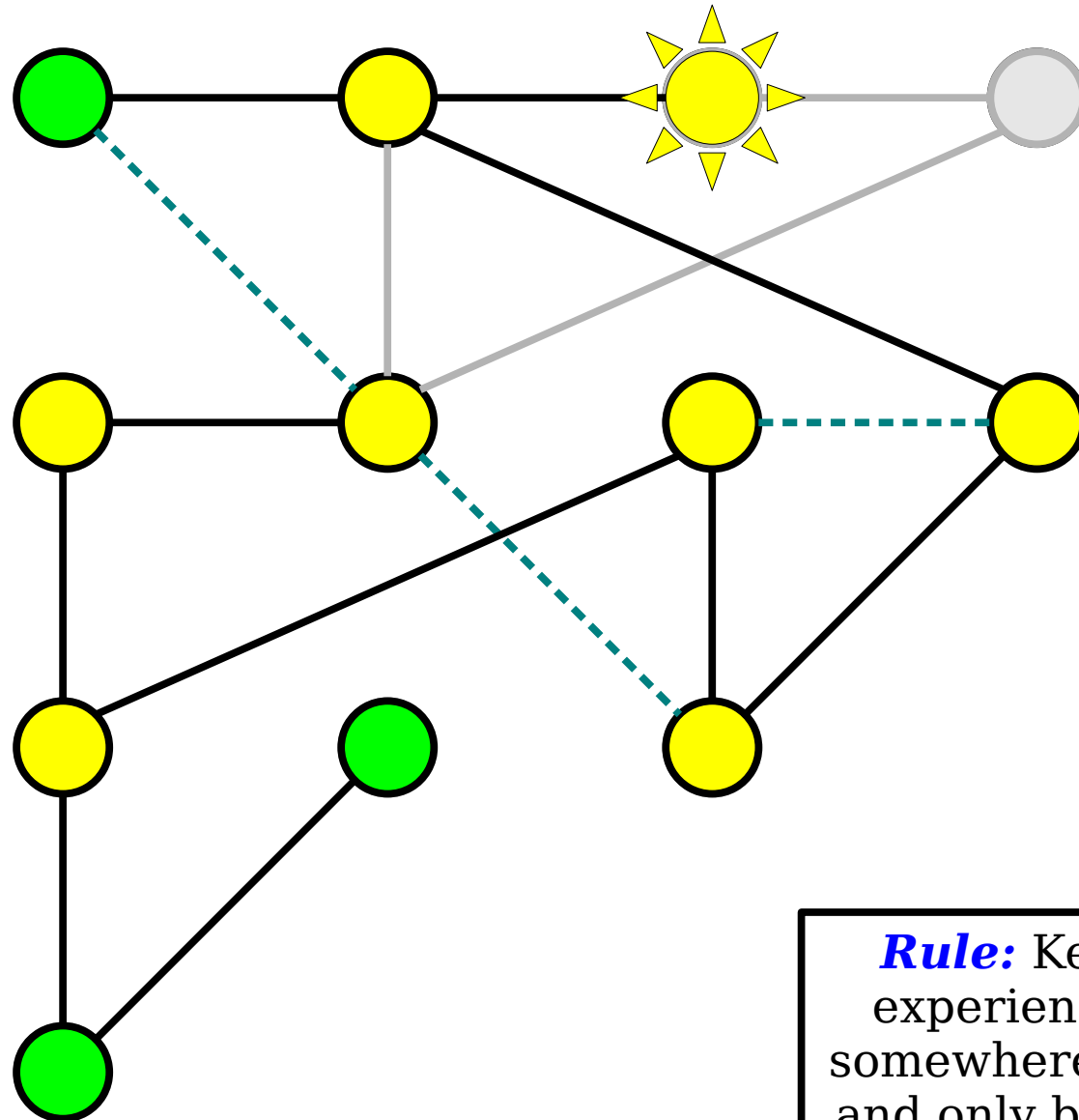
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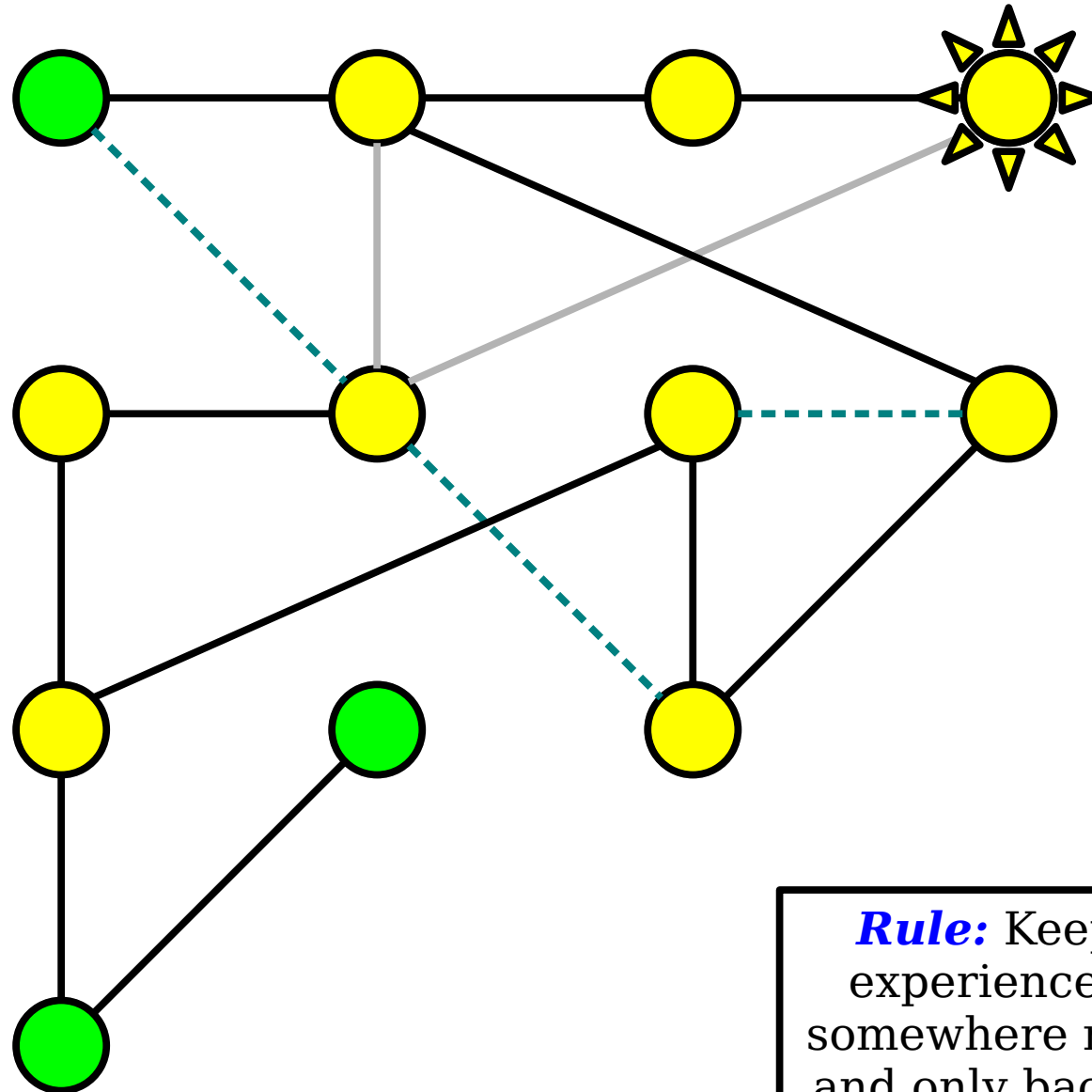
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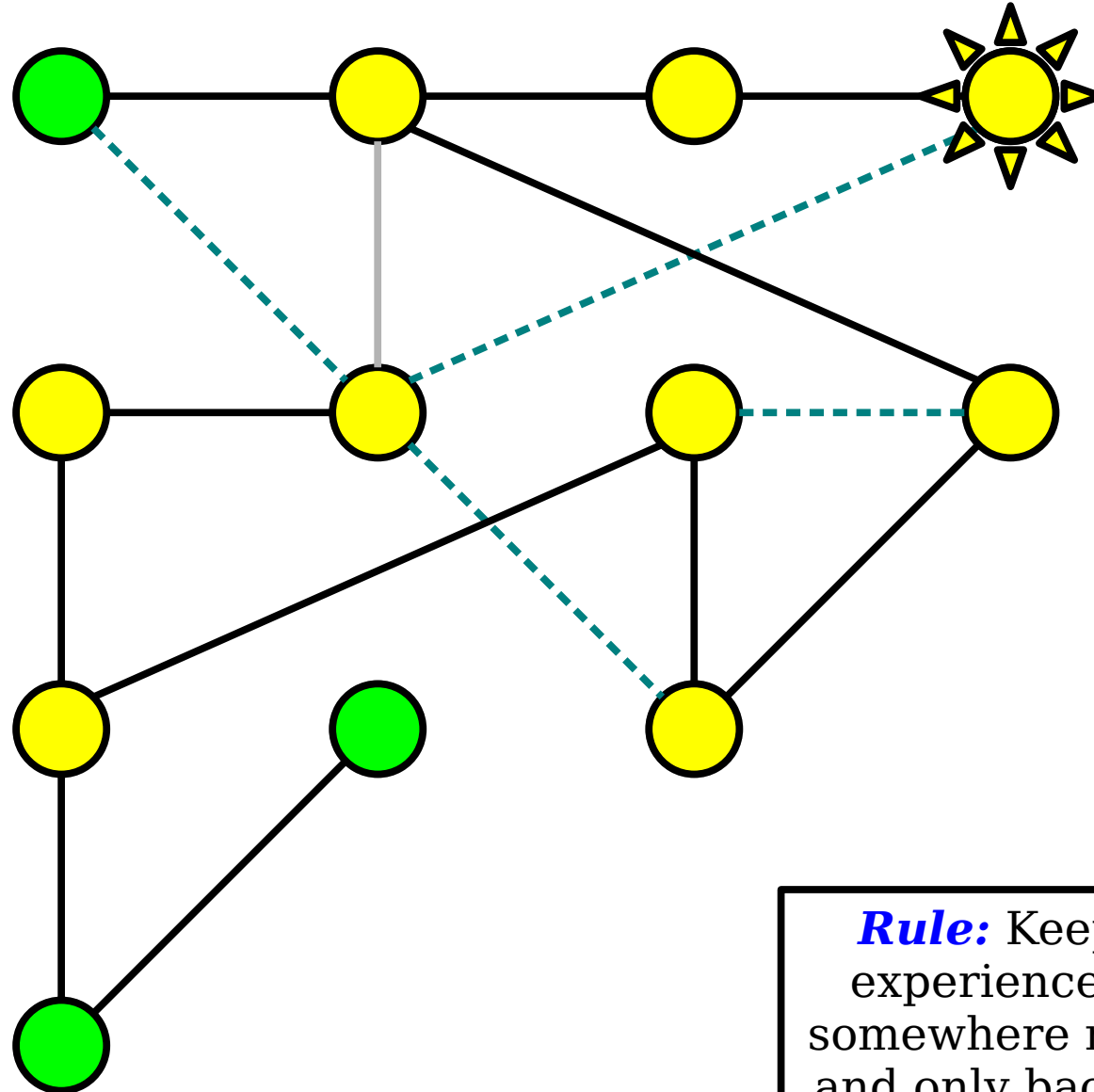
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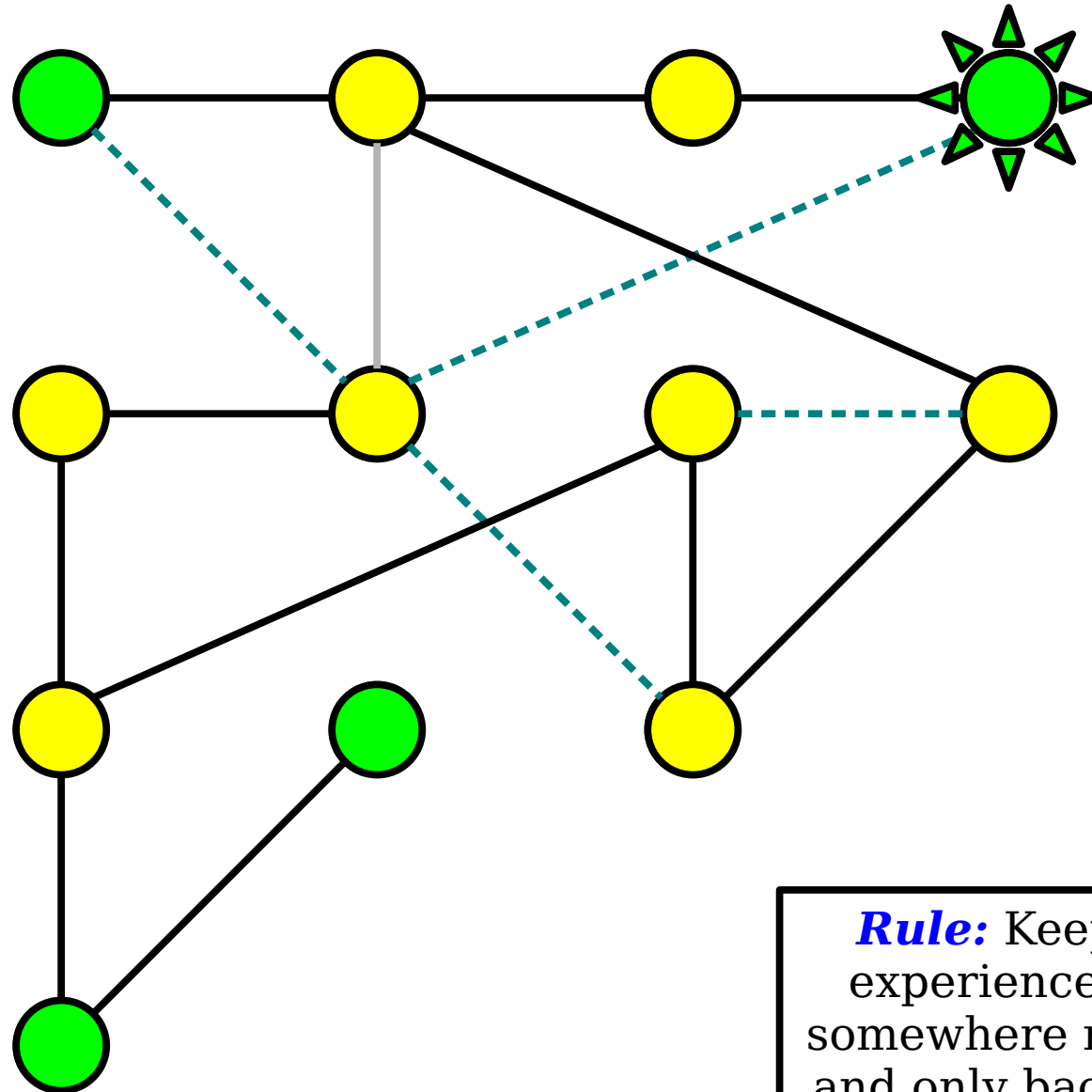
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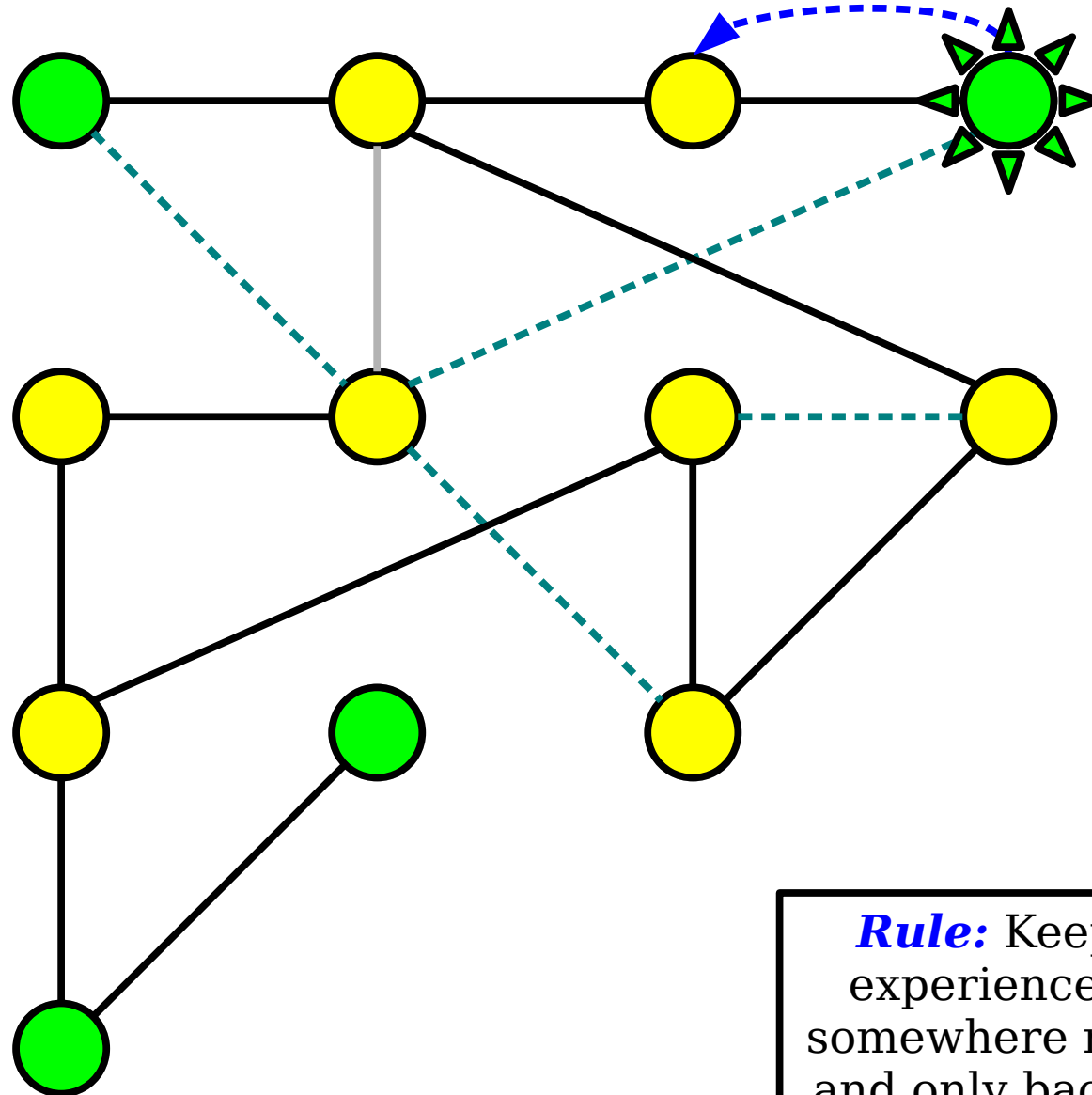
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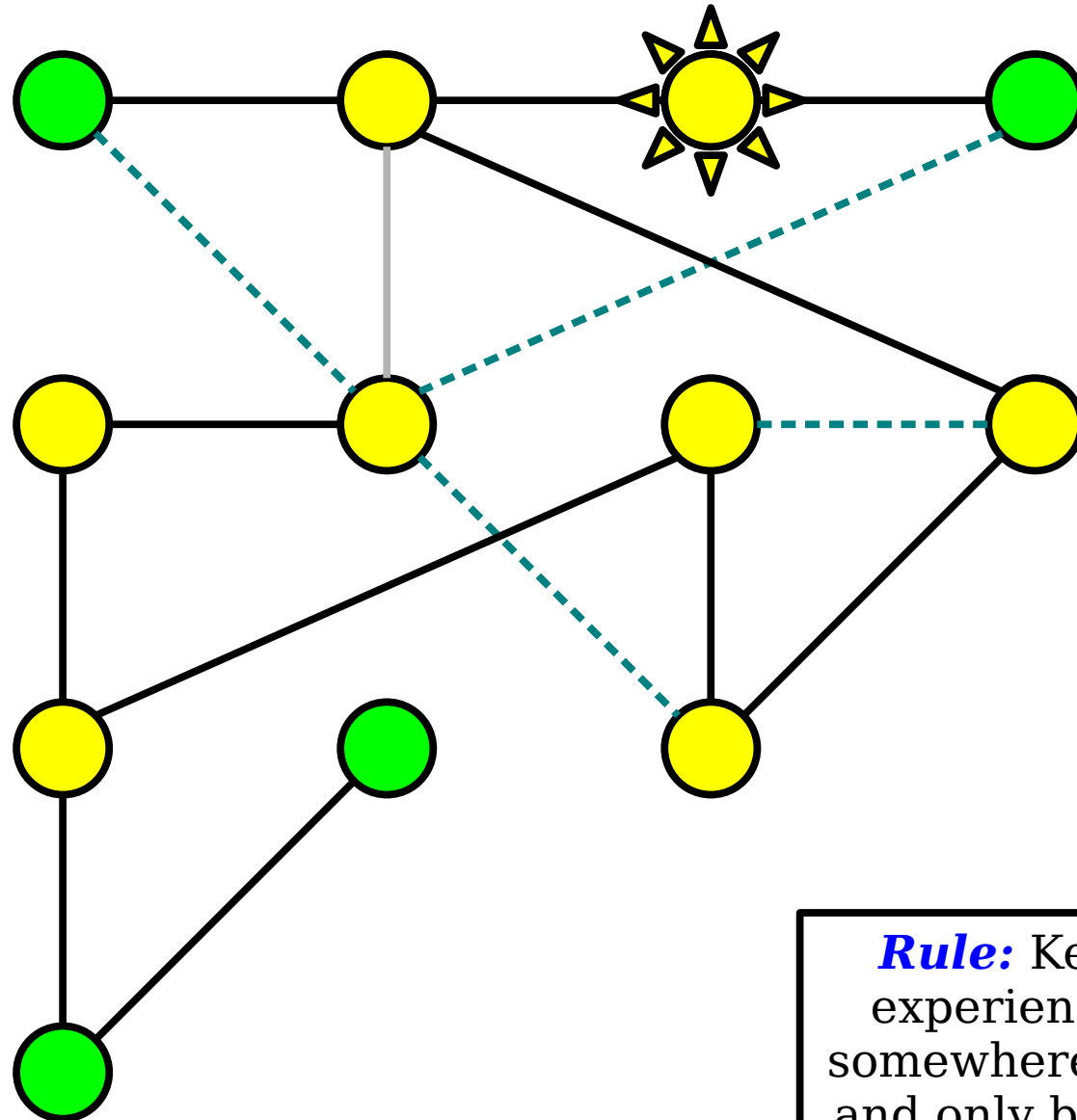
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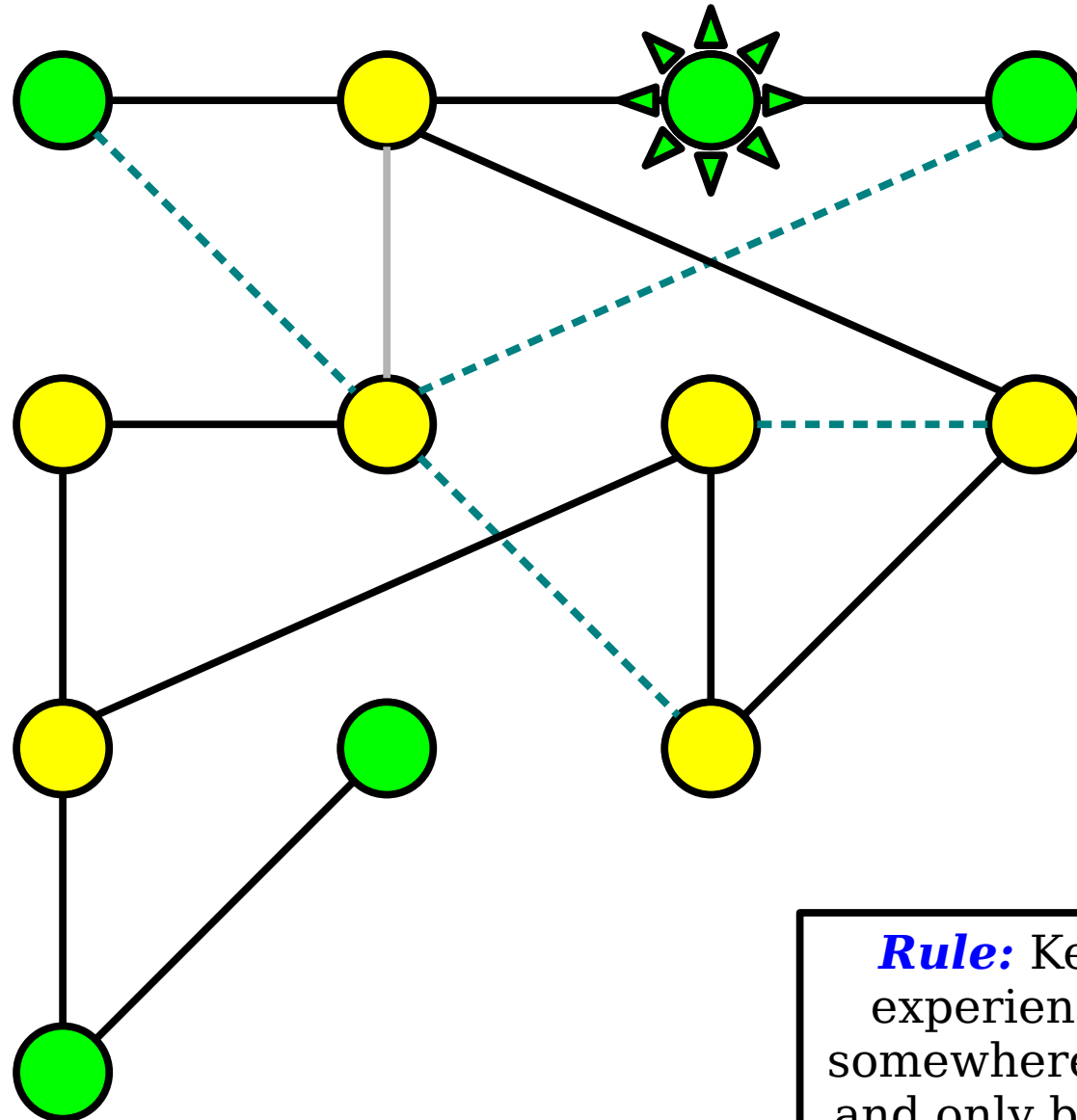
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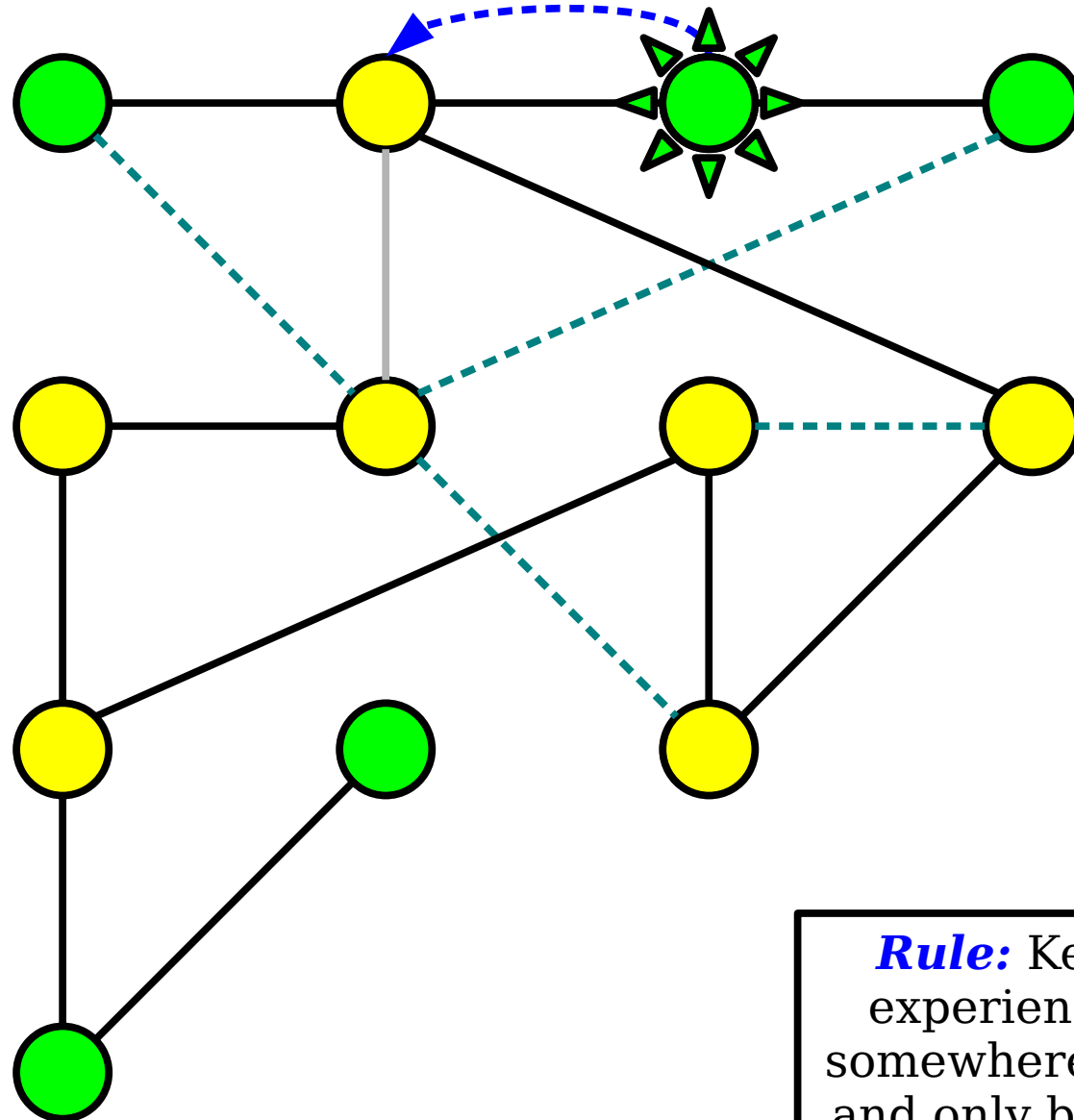
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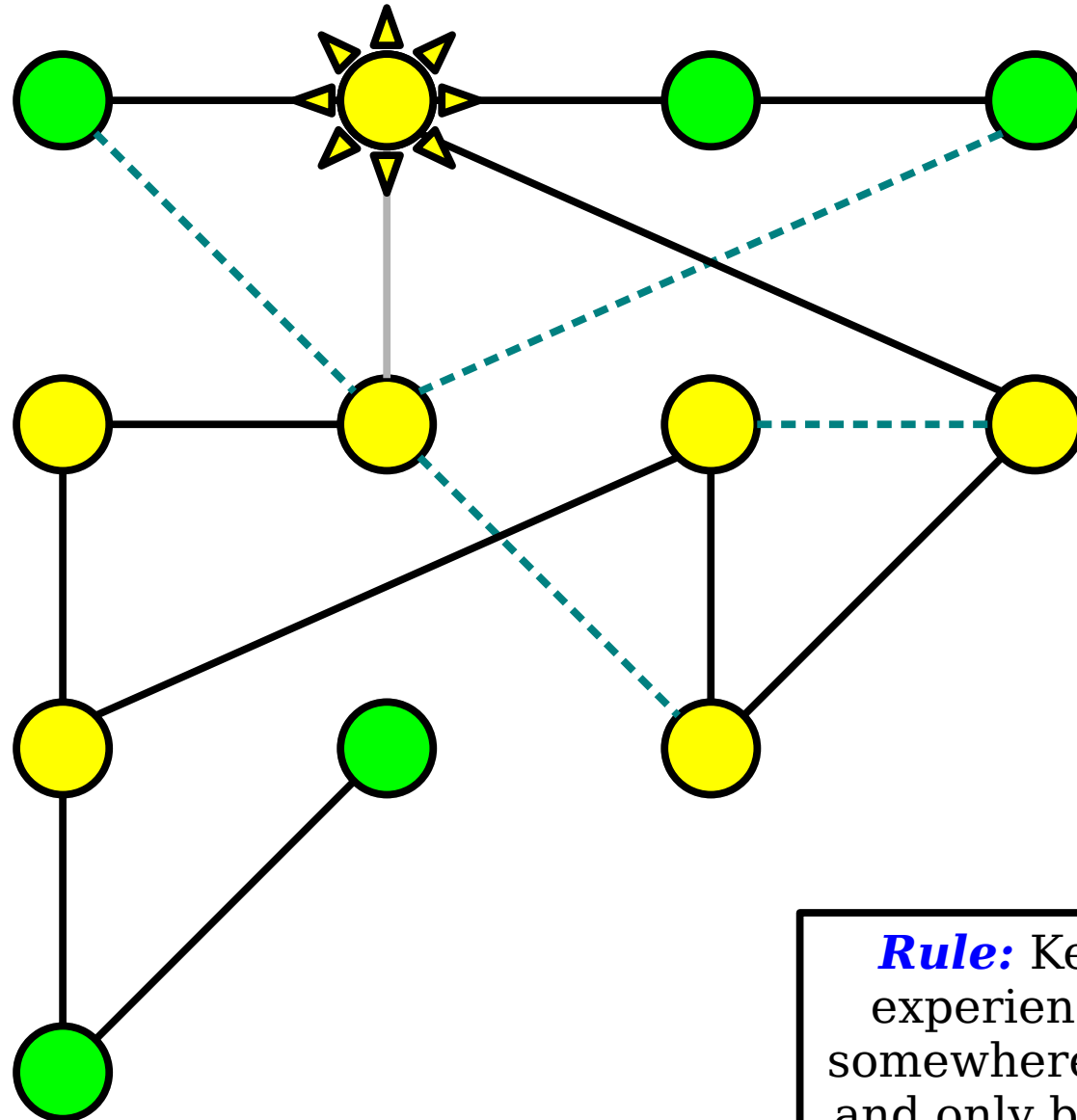
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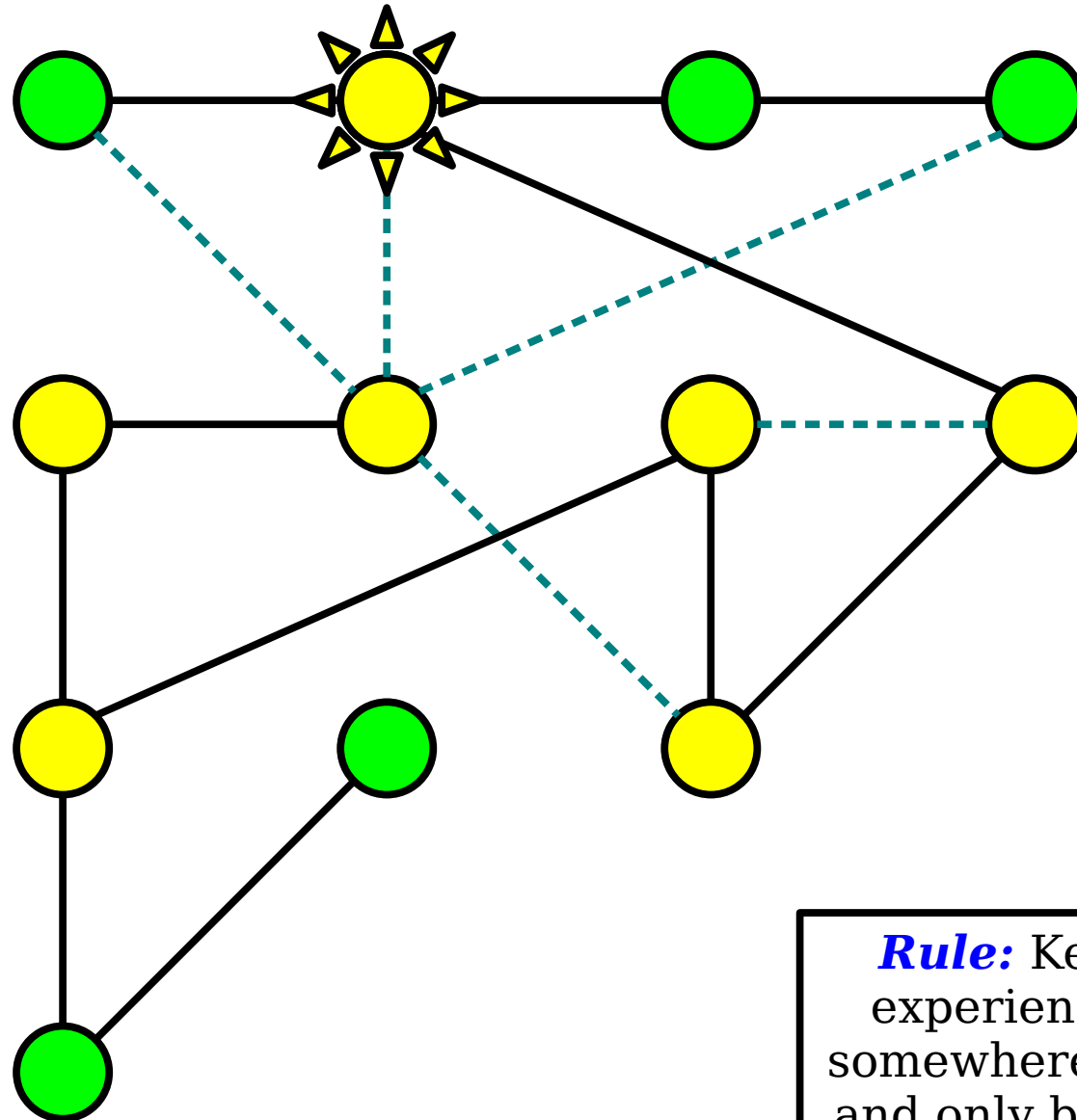
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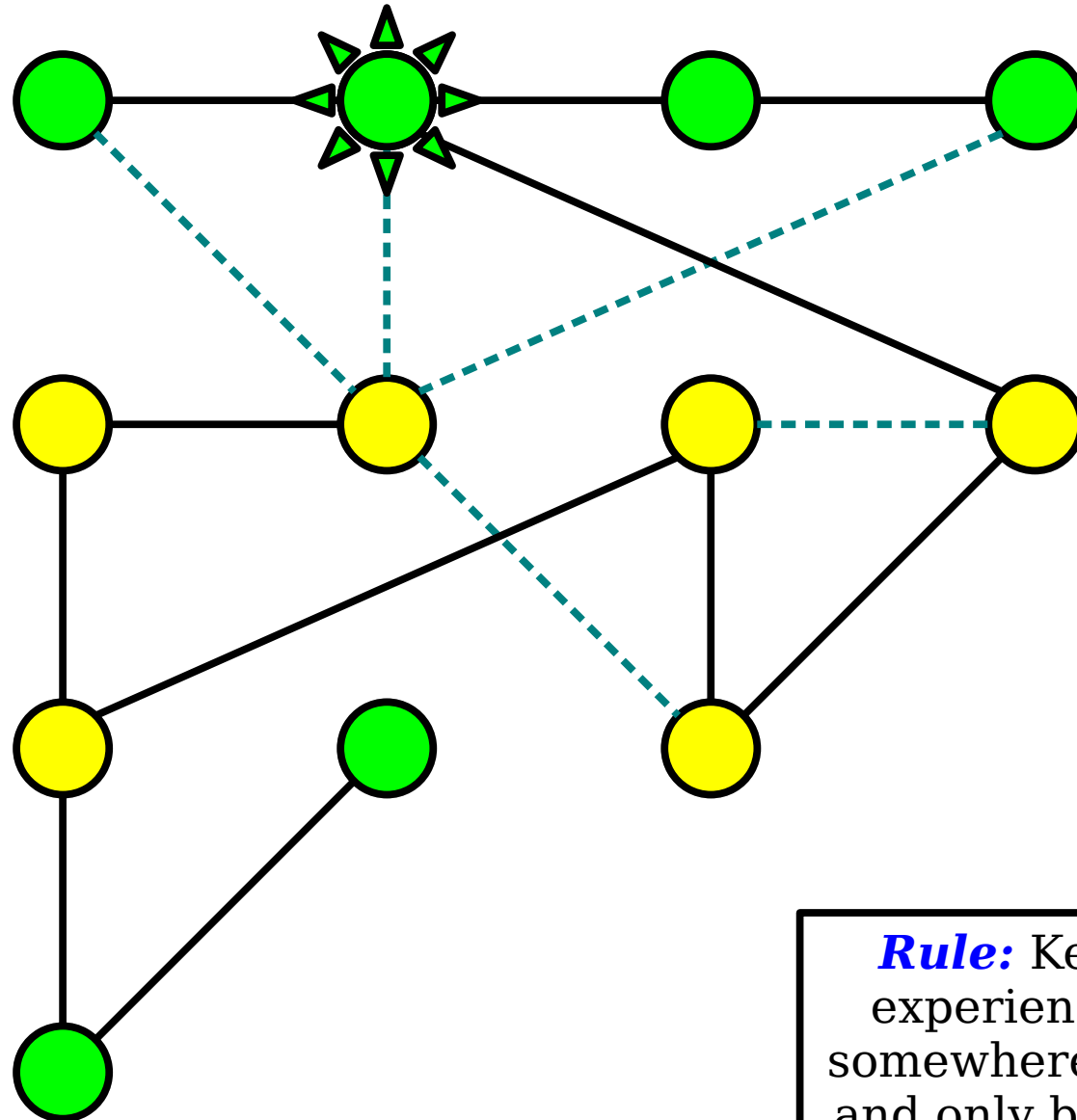
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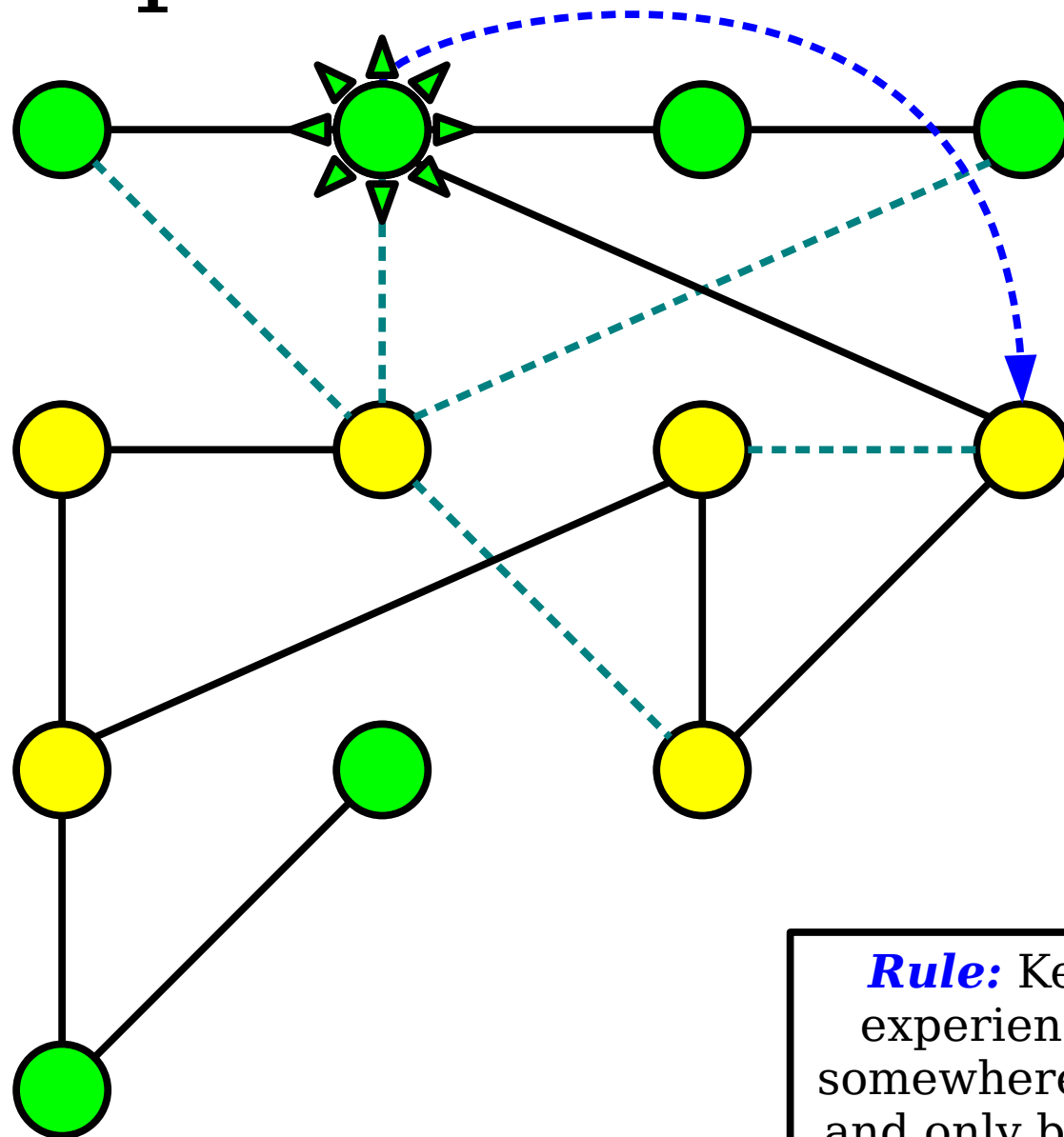
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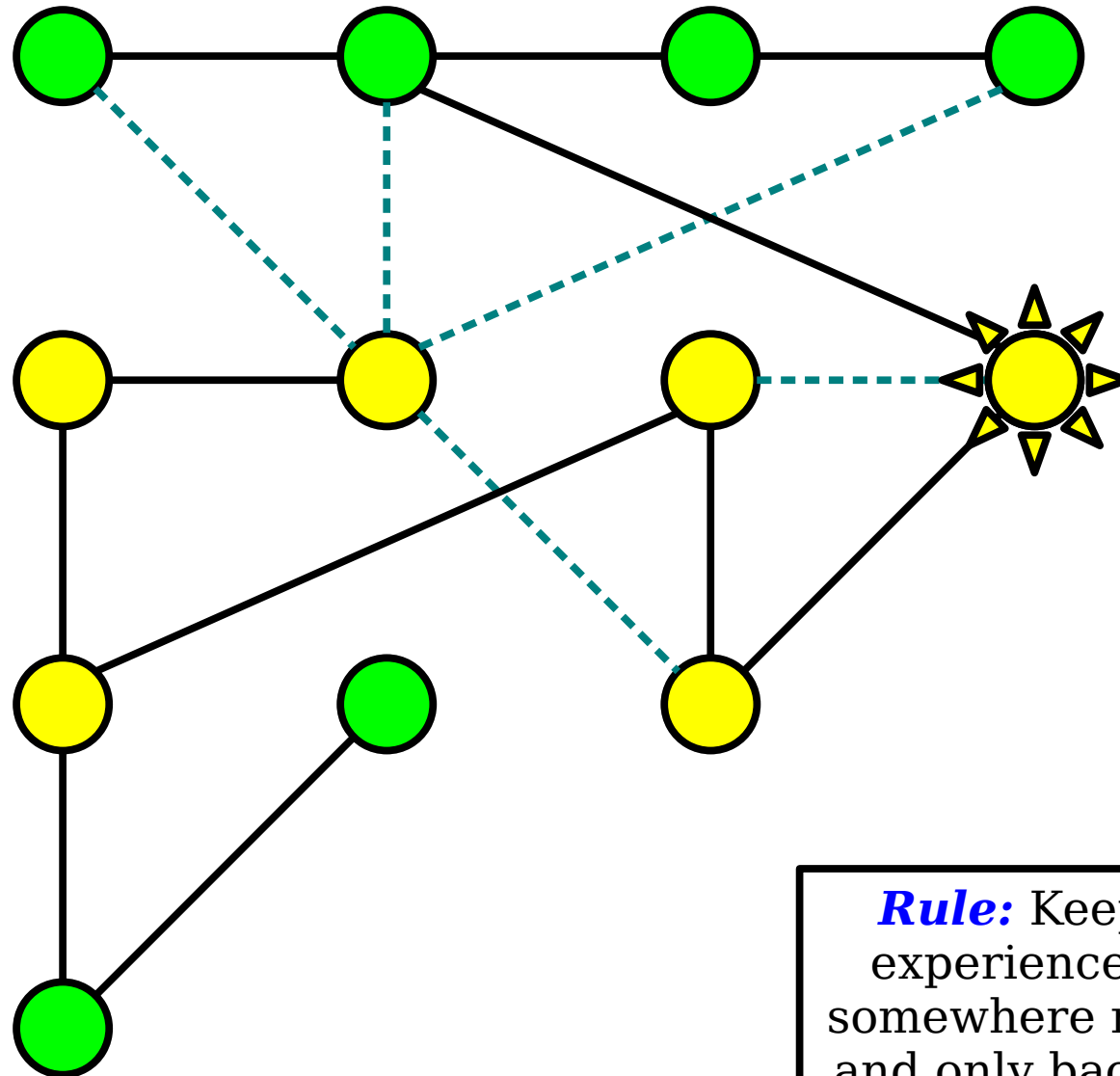
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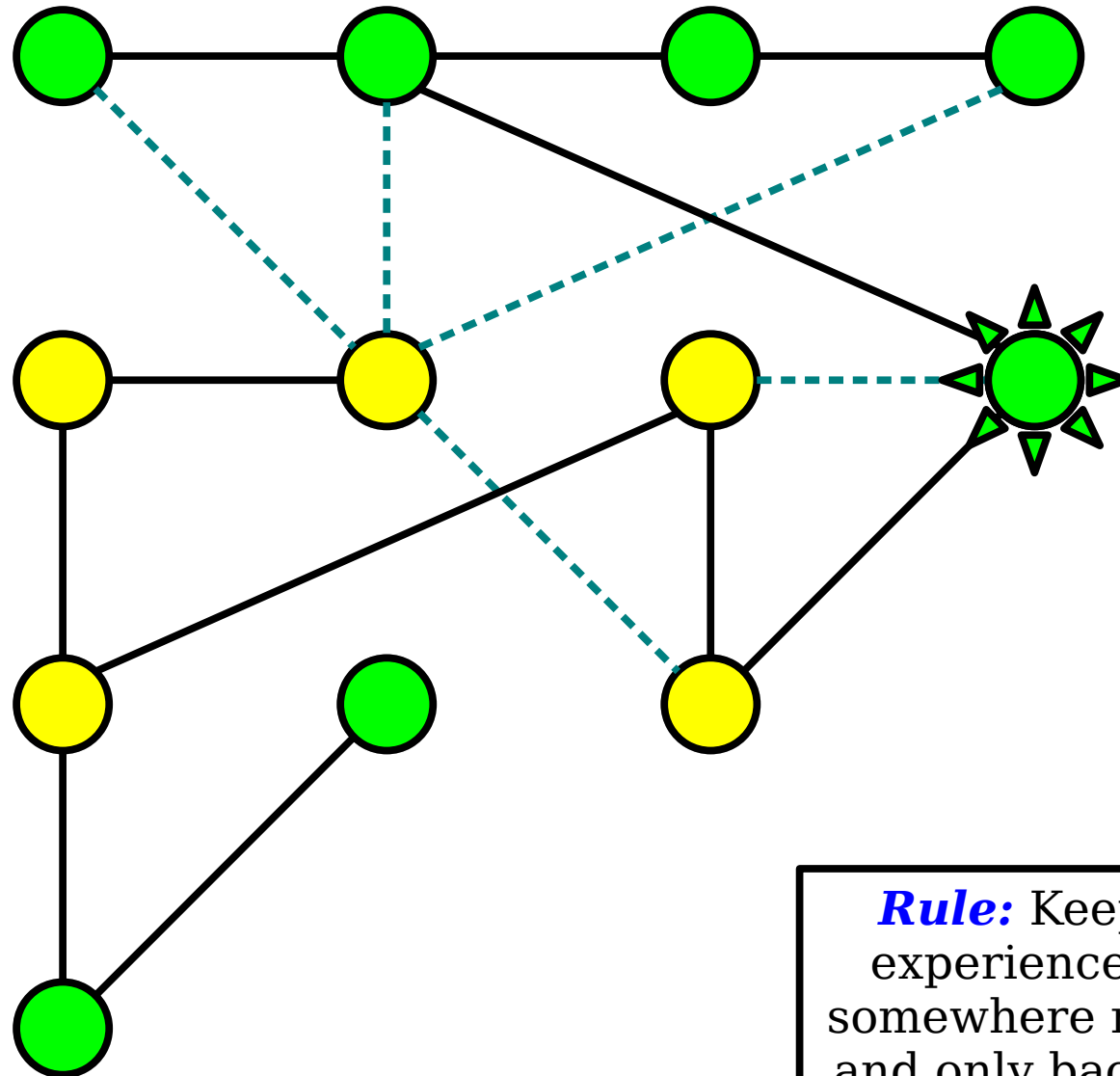
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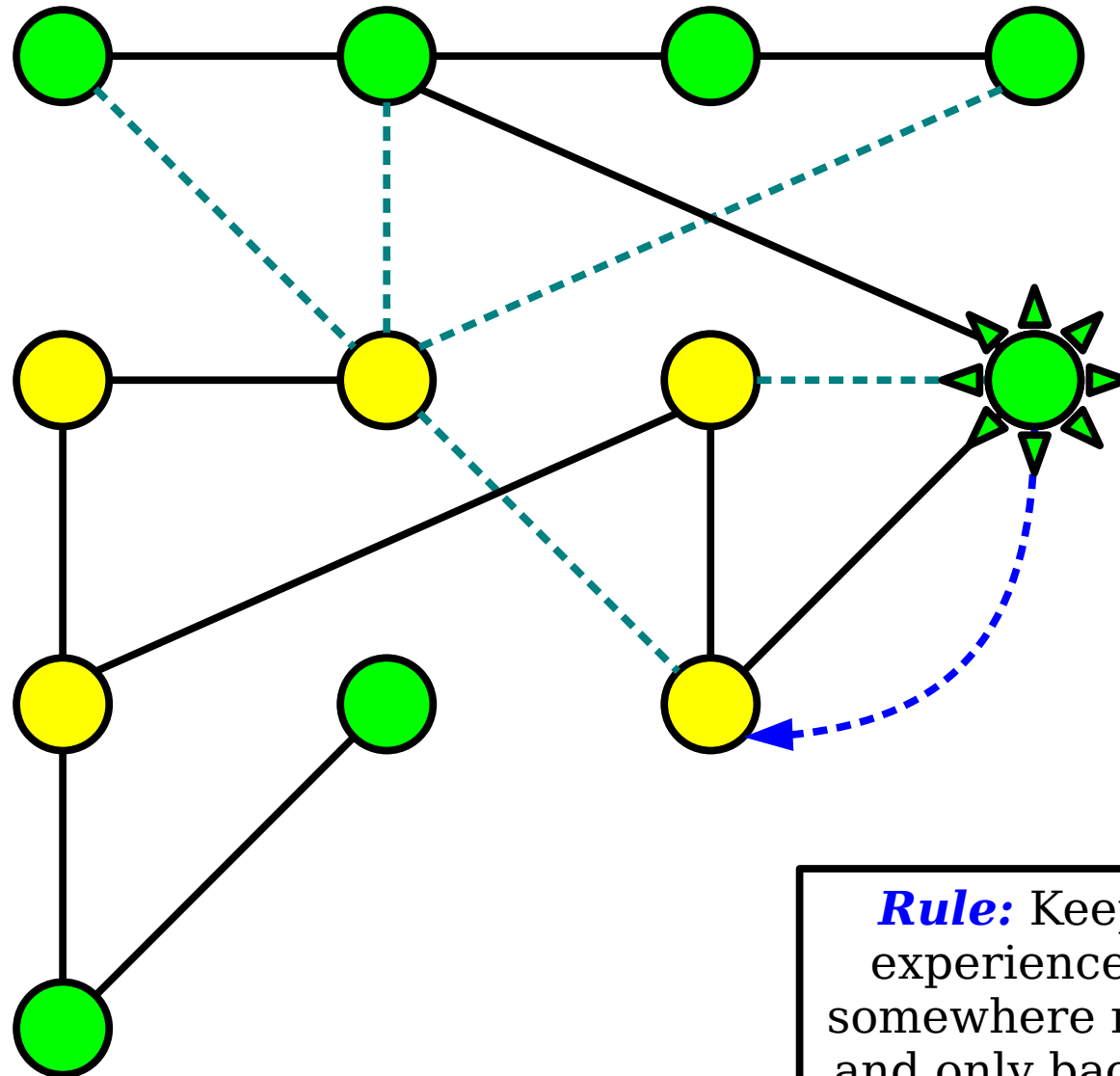
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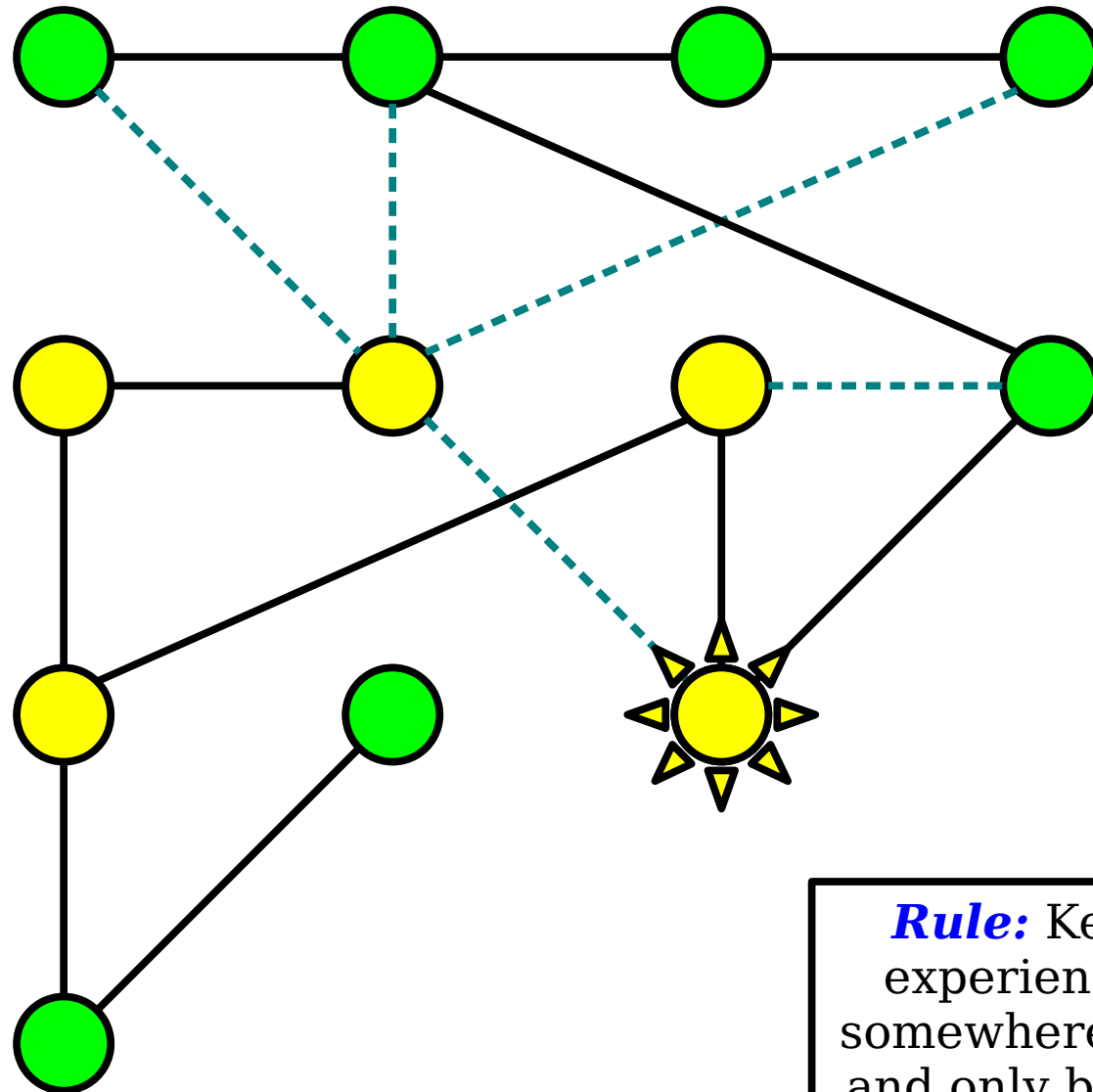
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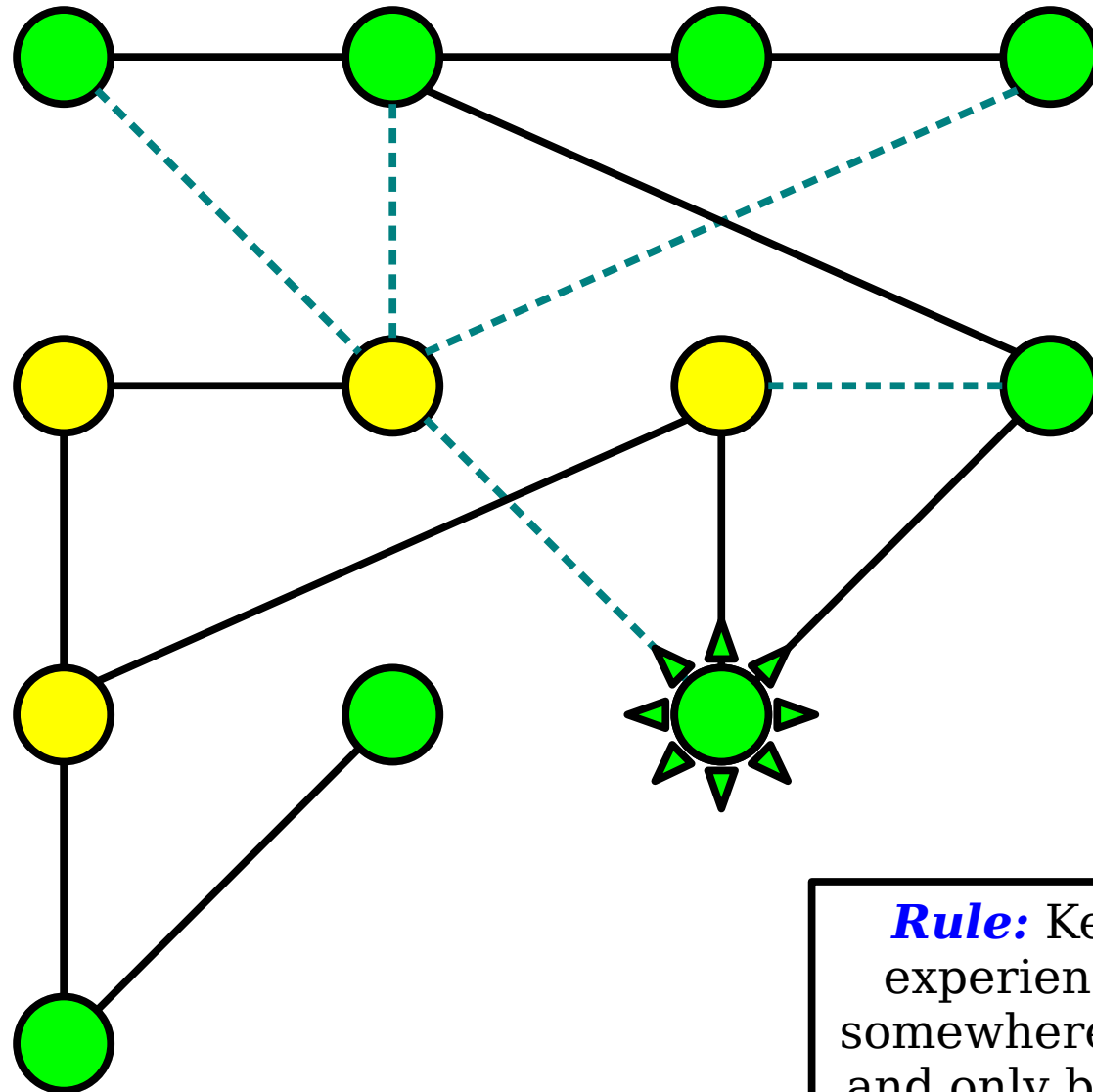
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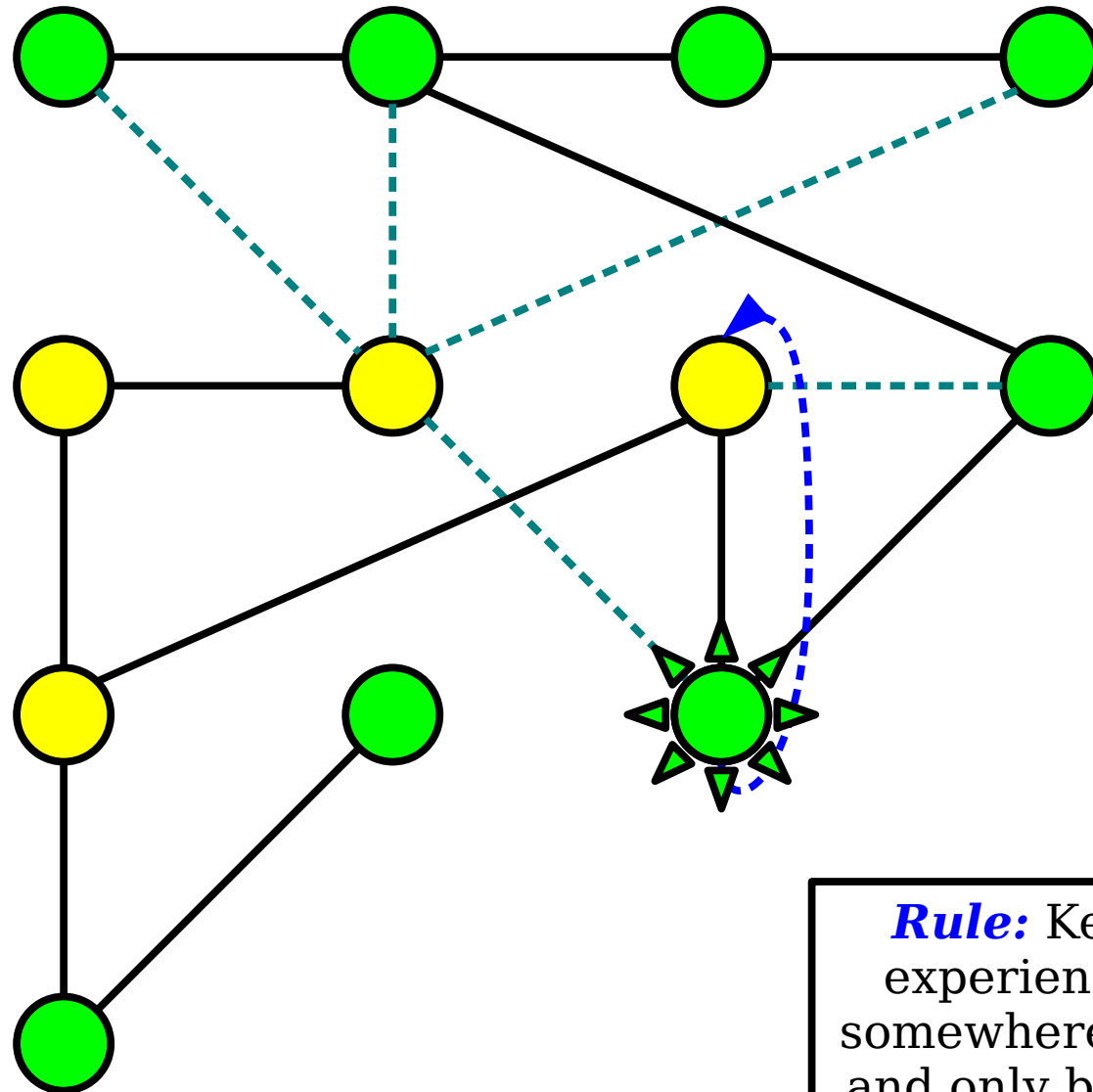
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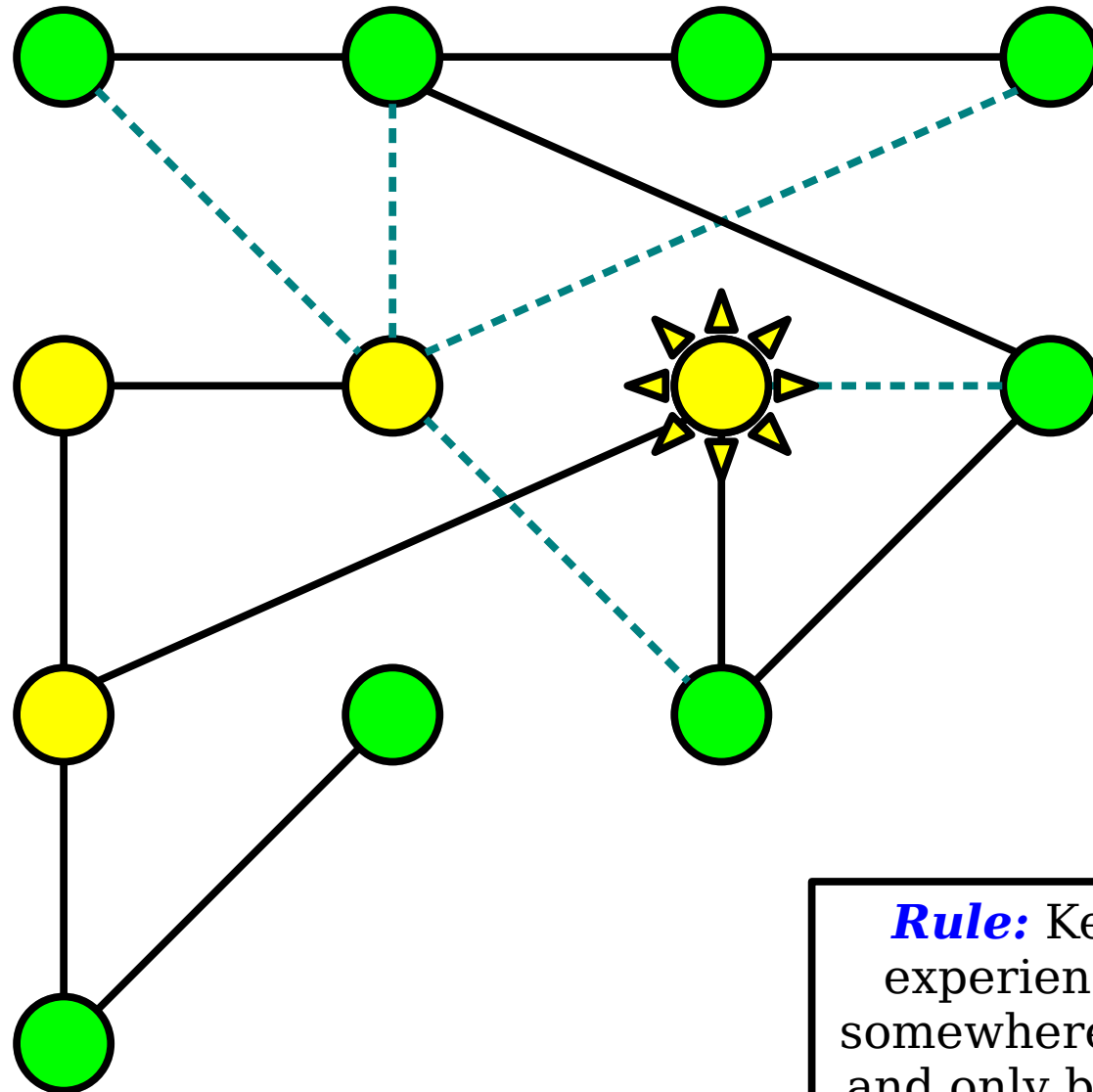
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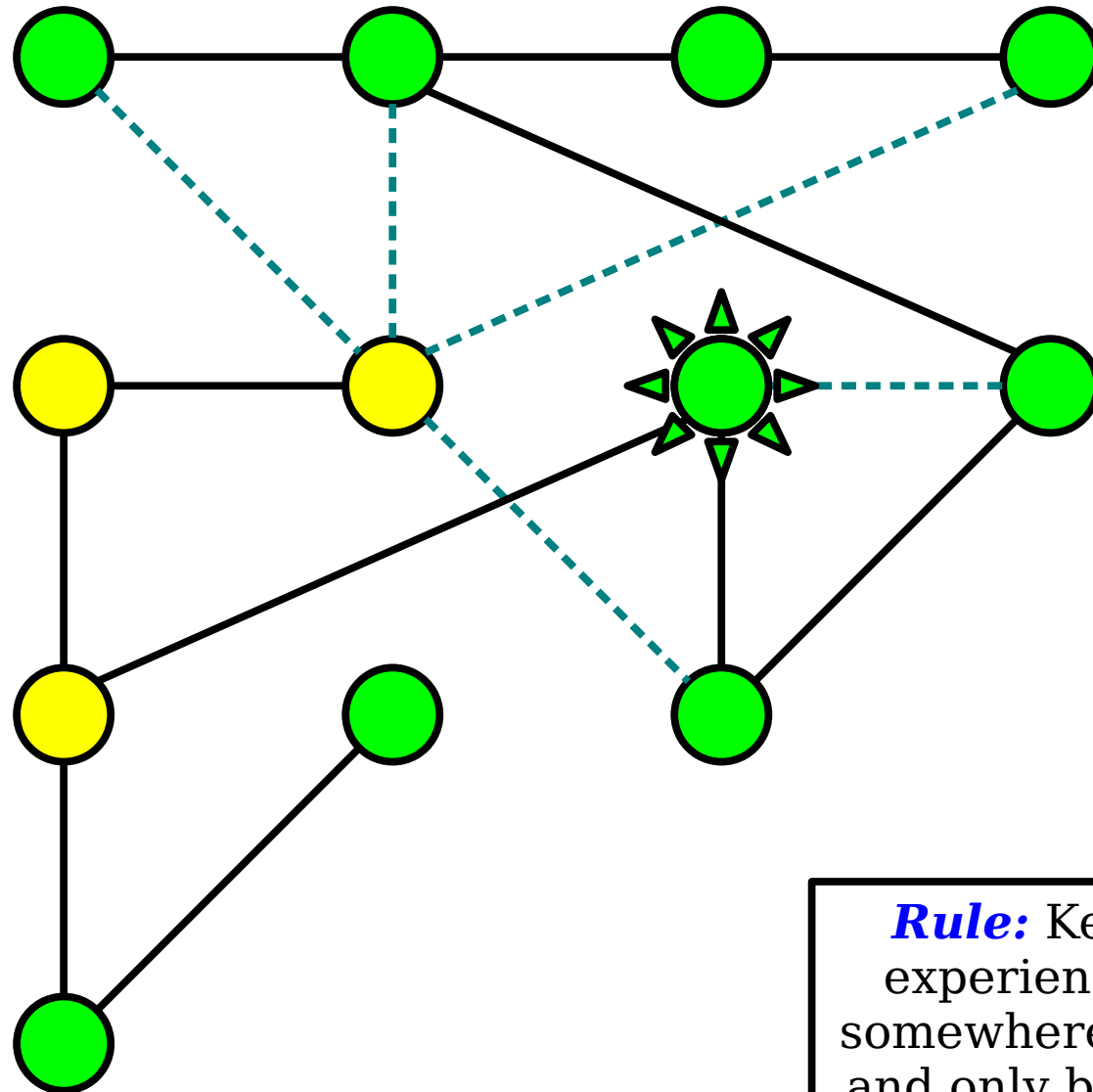
Rule: Keep trying new experiences! Always go somewhere new if you can, and only back up if there's nothing new to see.

Depth-First Search



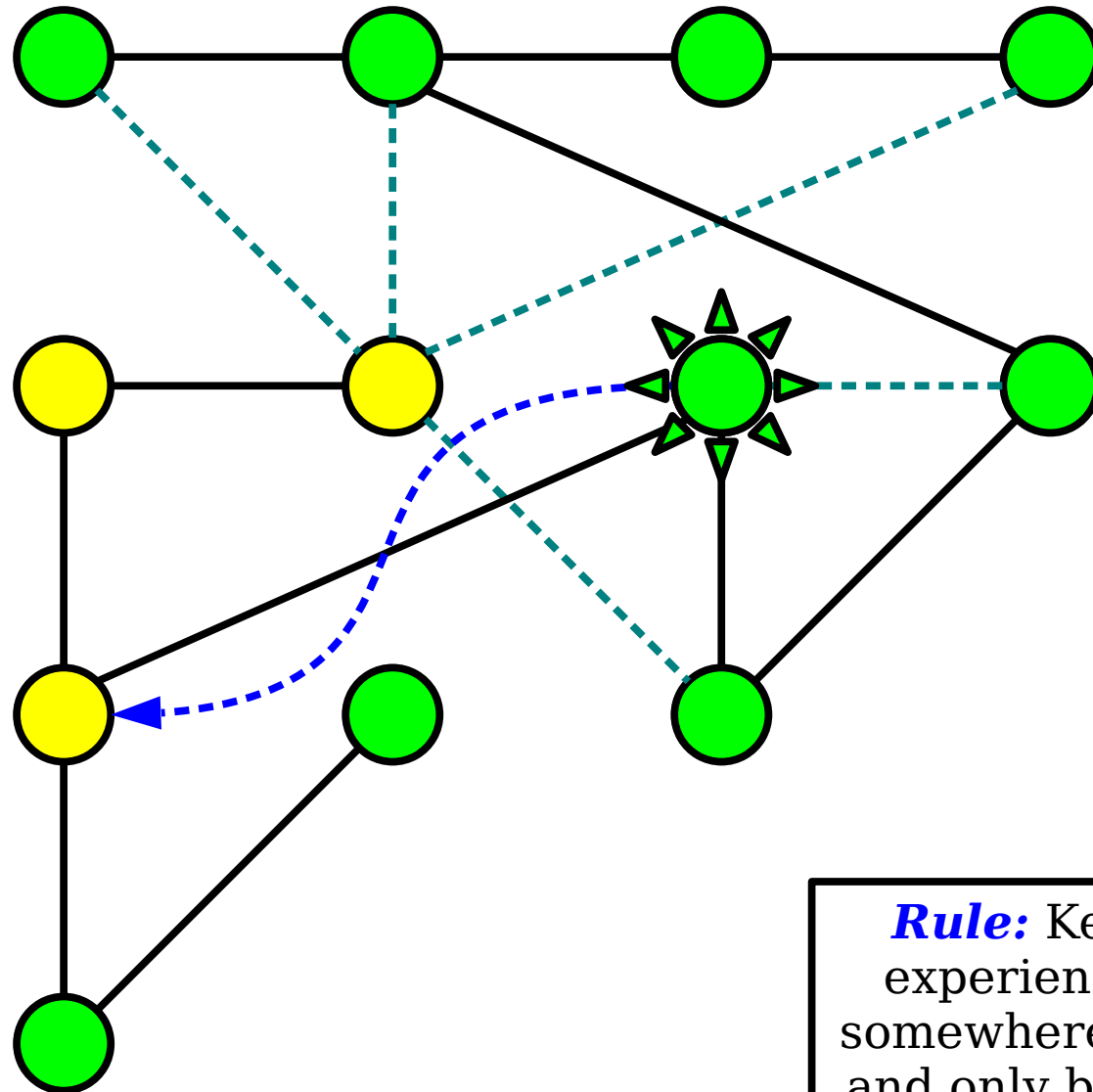
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Depth-First Search



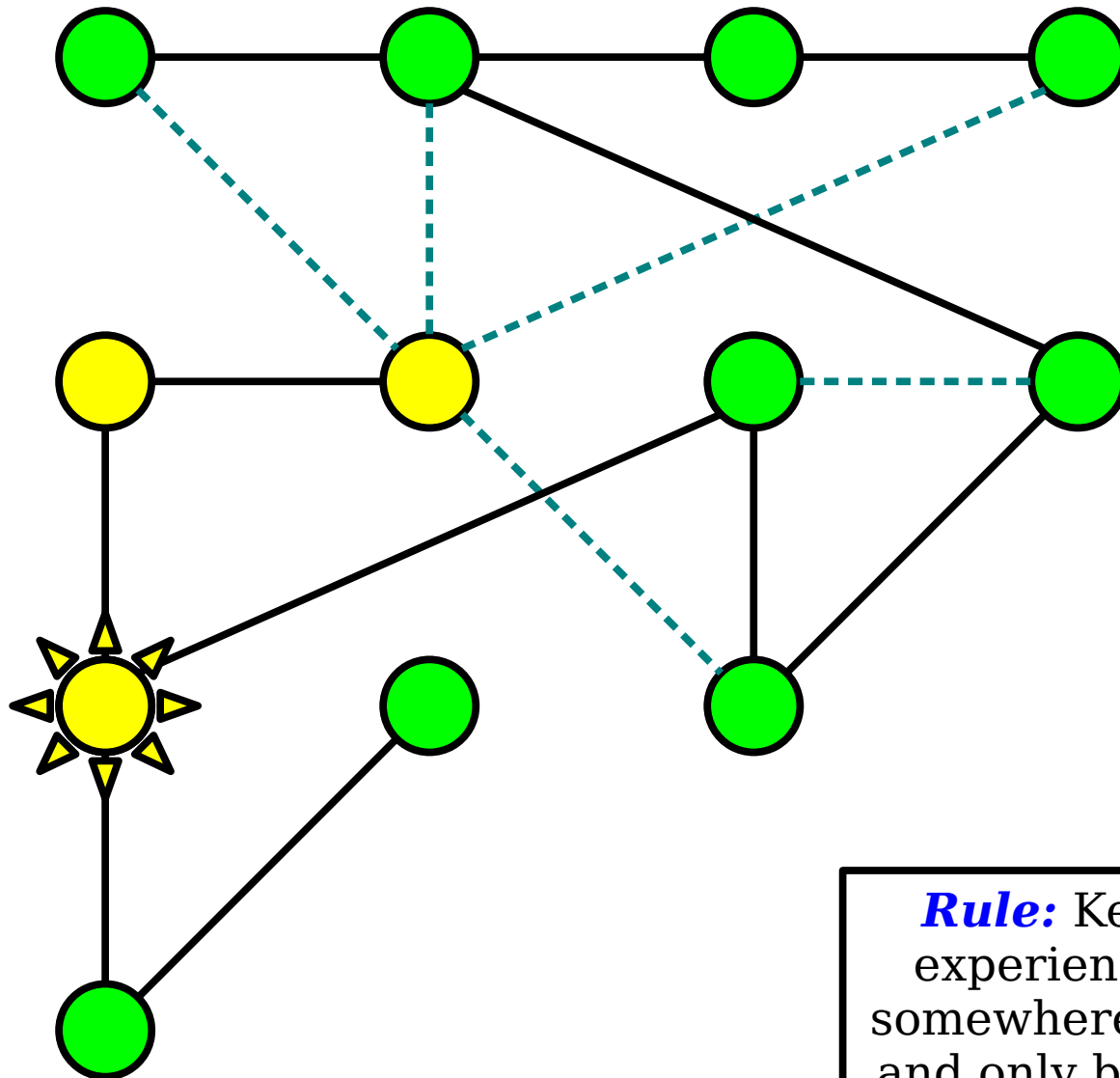
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Depth-First Search



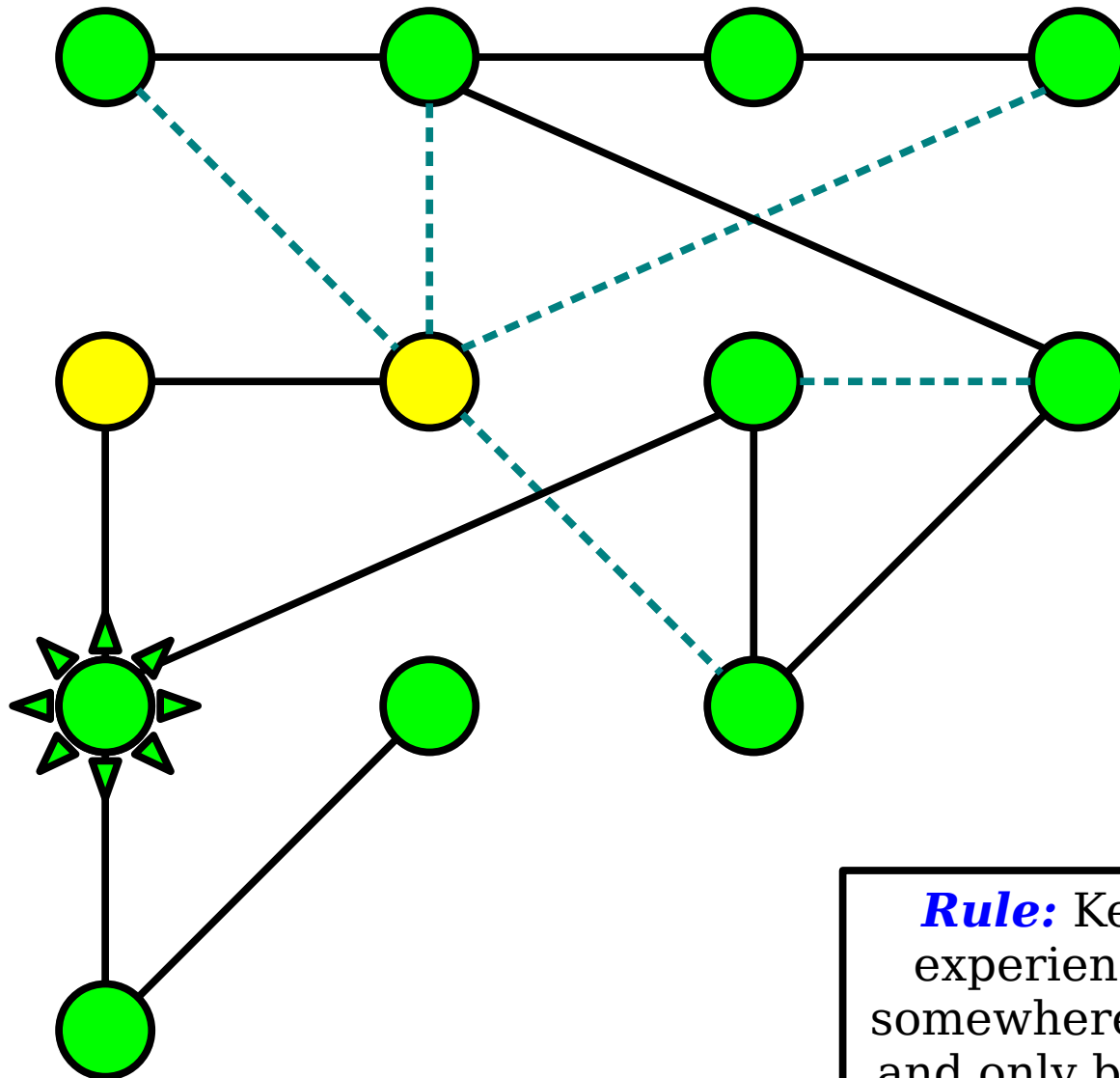
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Depth-First Search



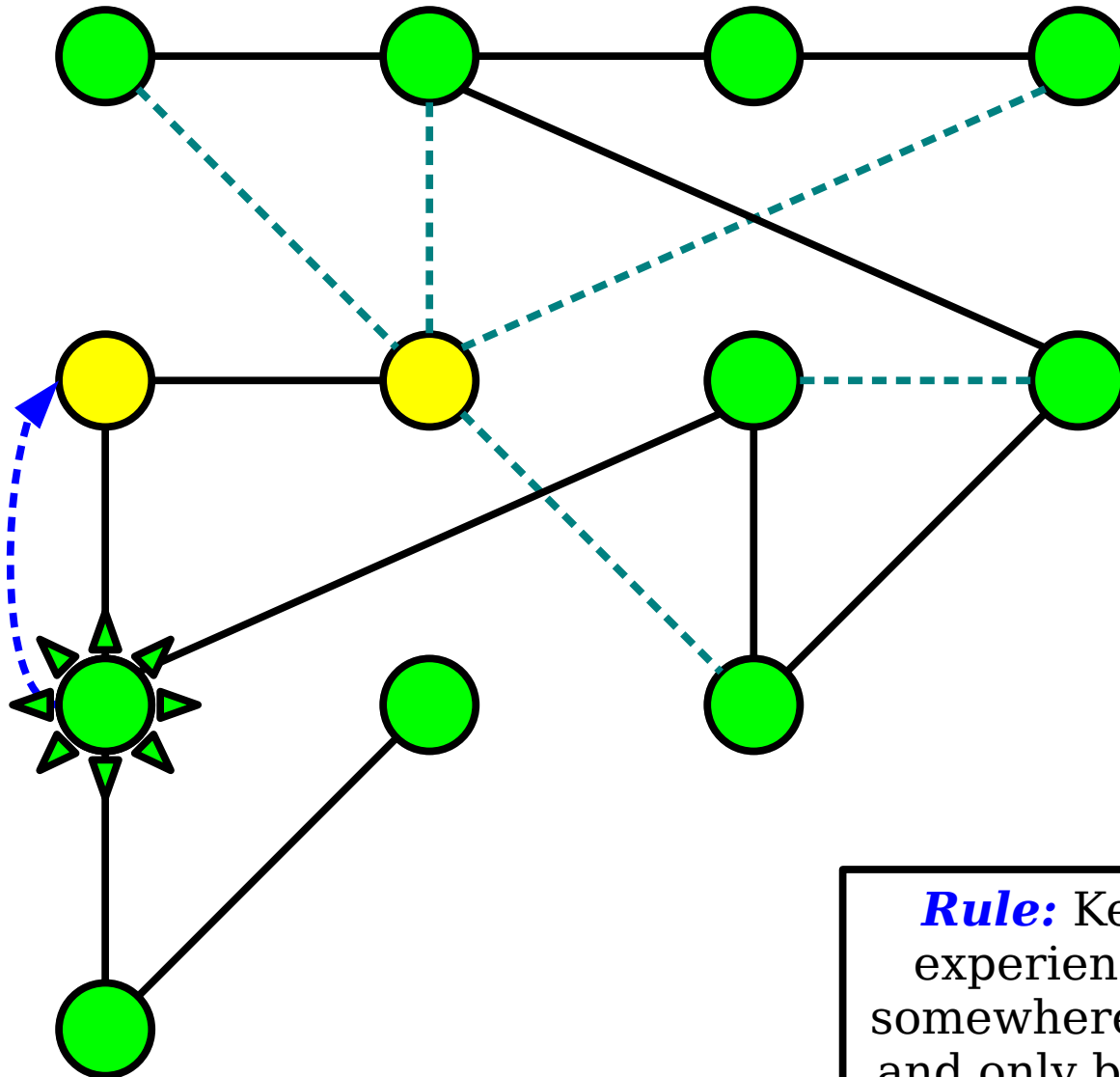
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Depth-First Search



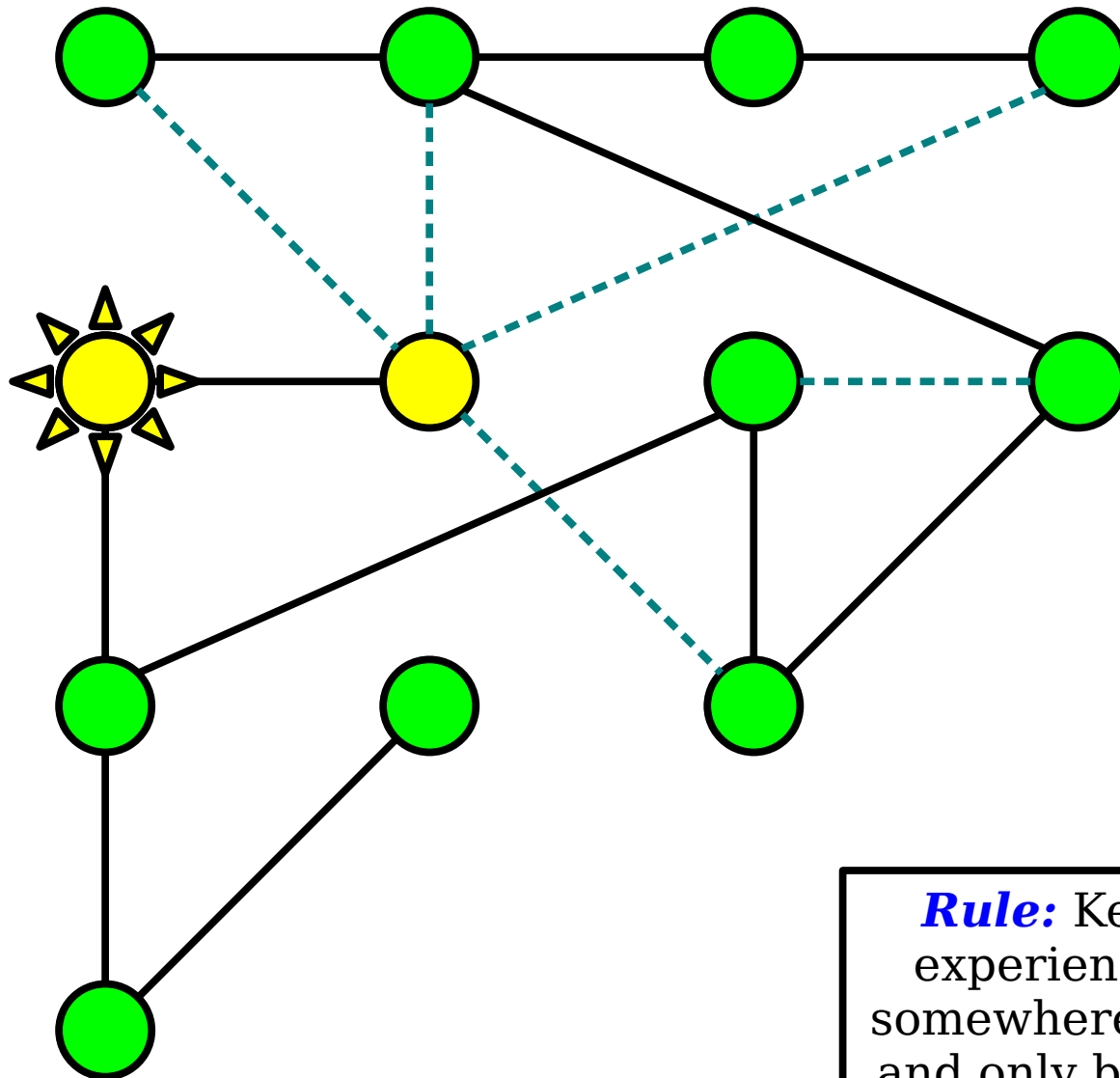
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Depth-First Search



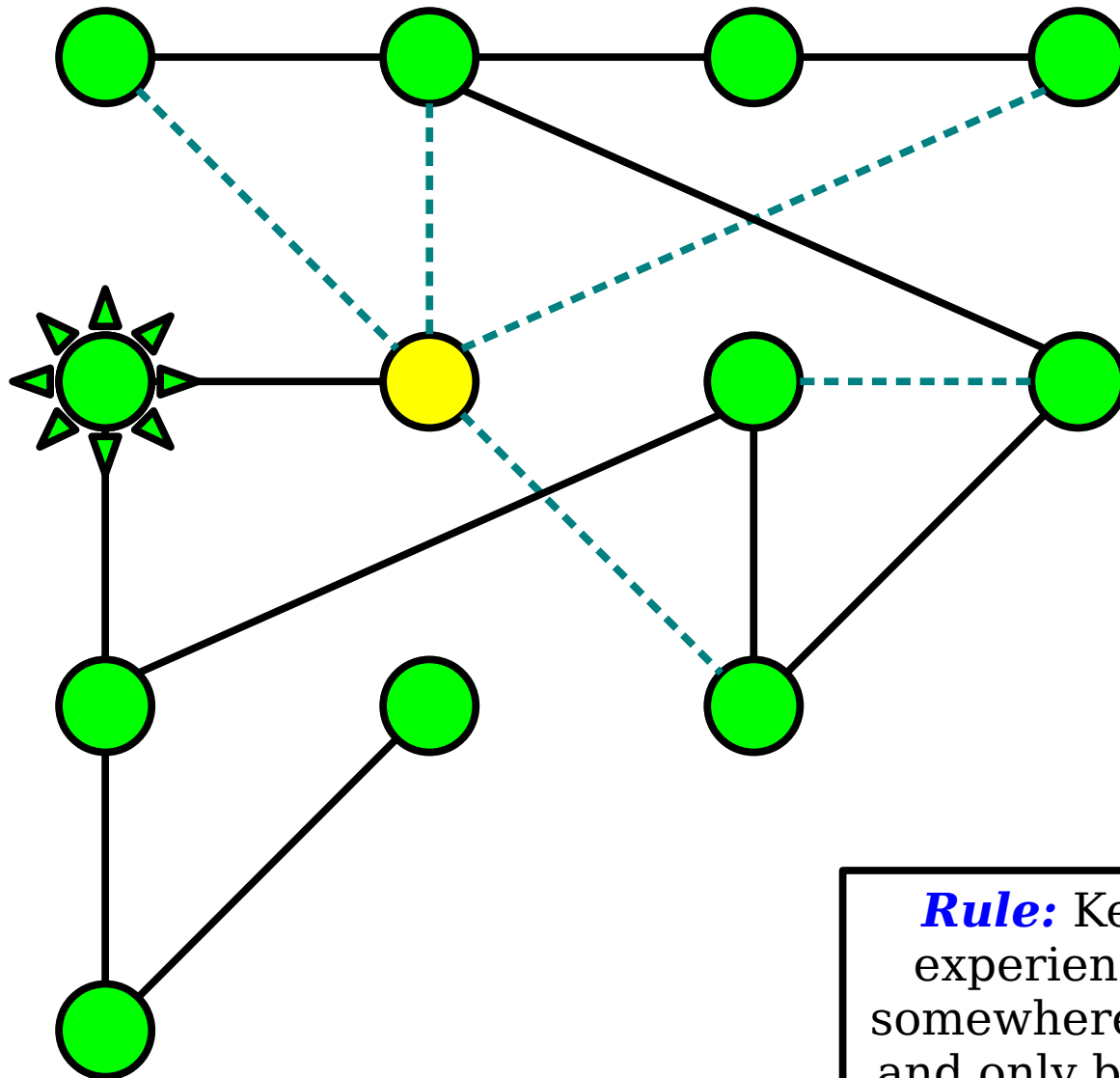
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Depth-First Search



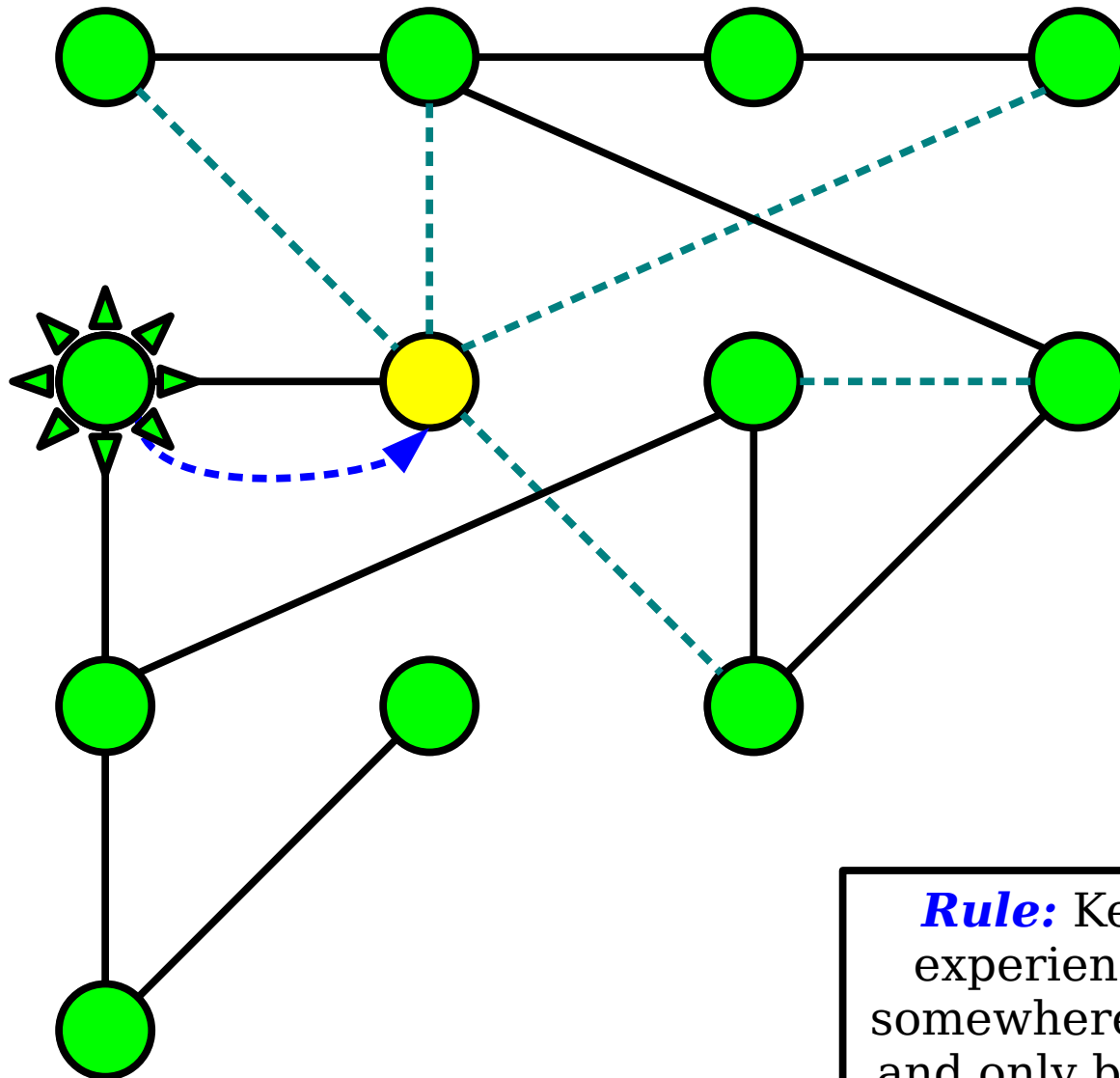
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Depth-First Search



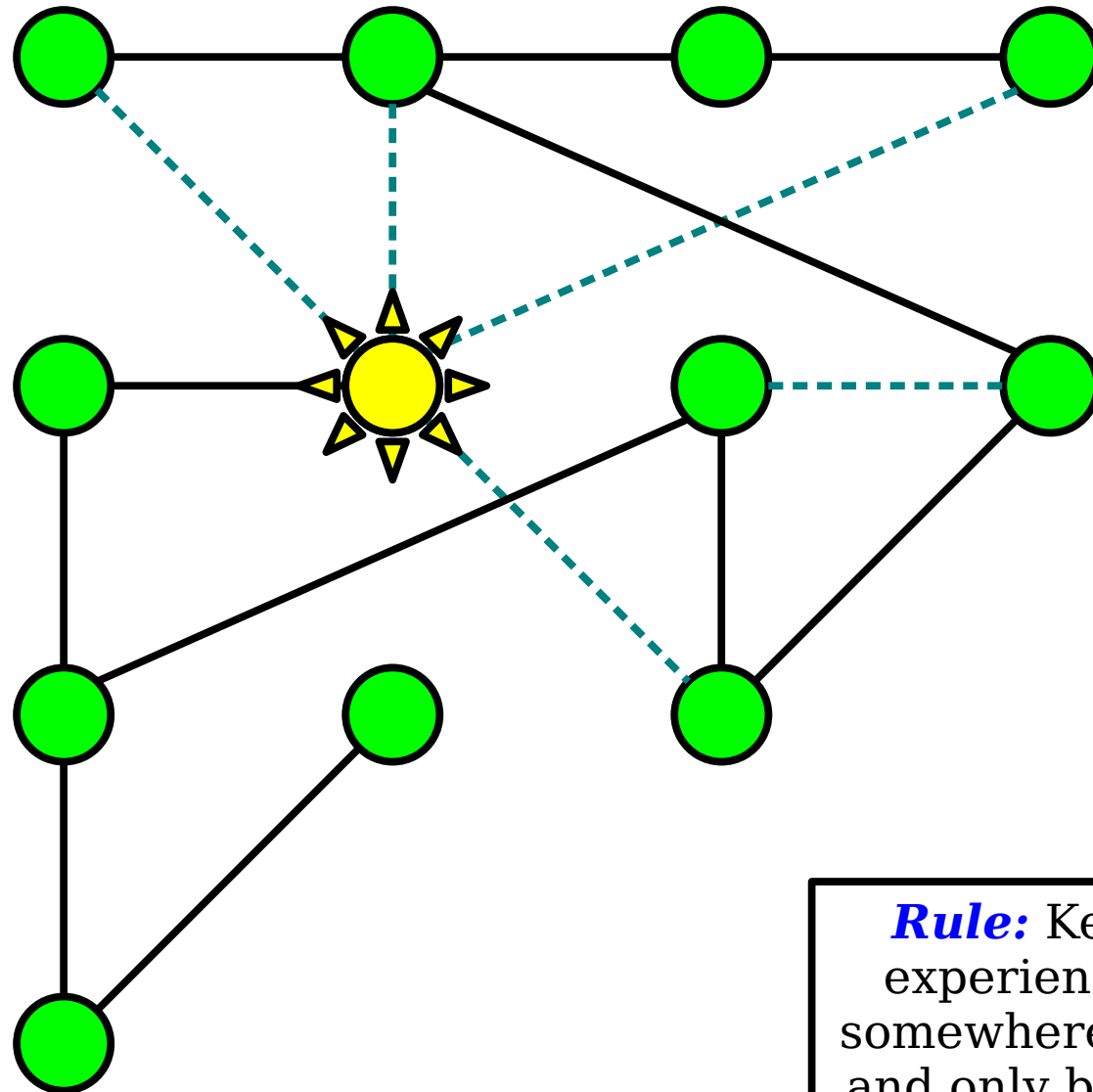
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Depth-First Search



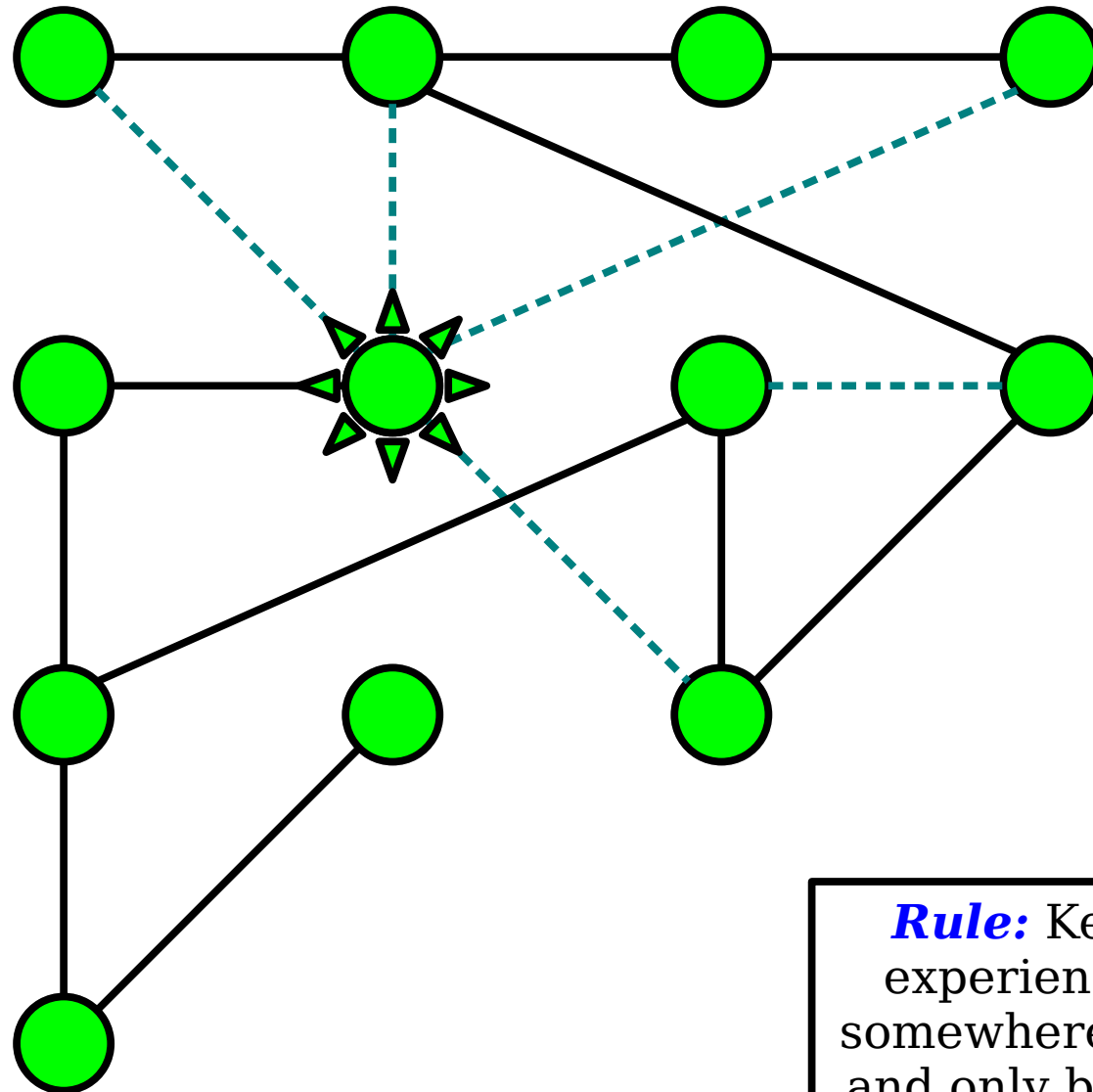
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Depth-First Search



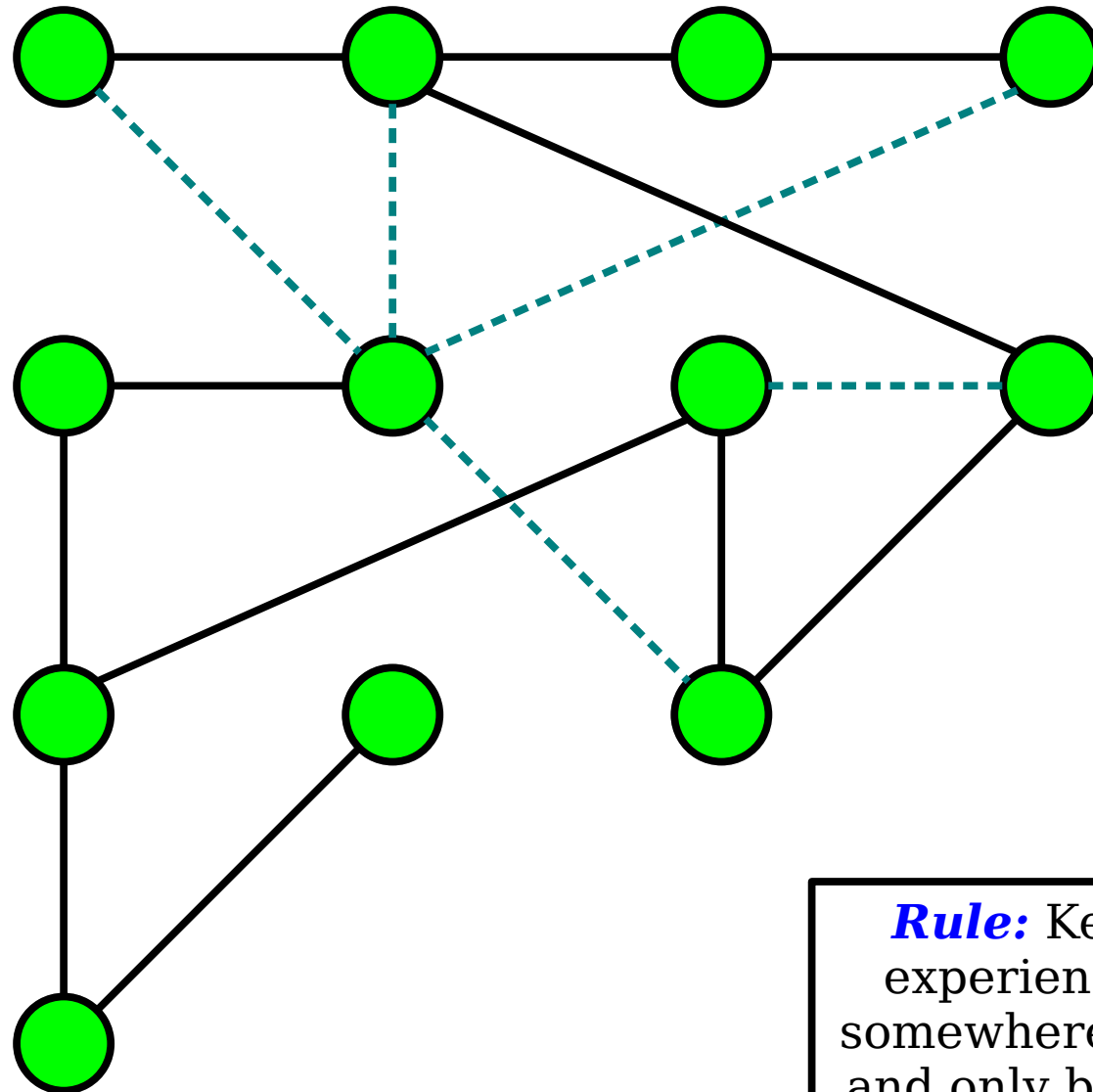
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Depth-First Search



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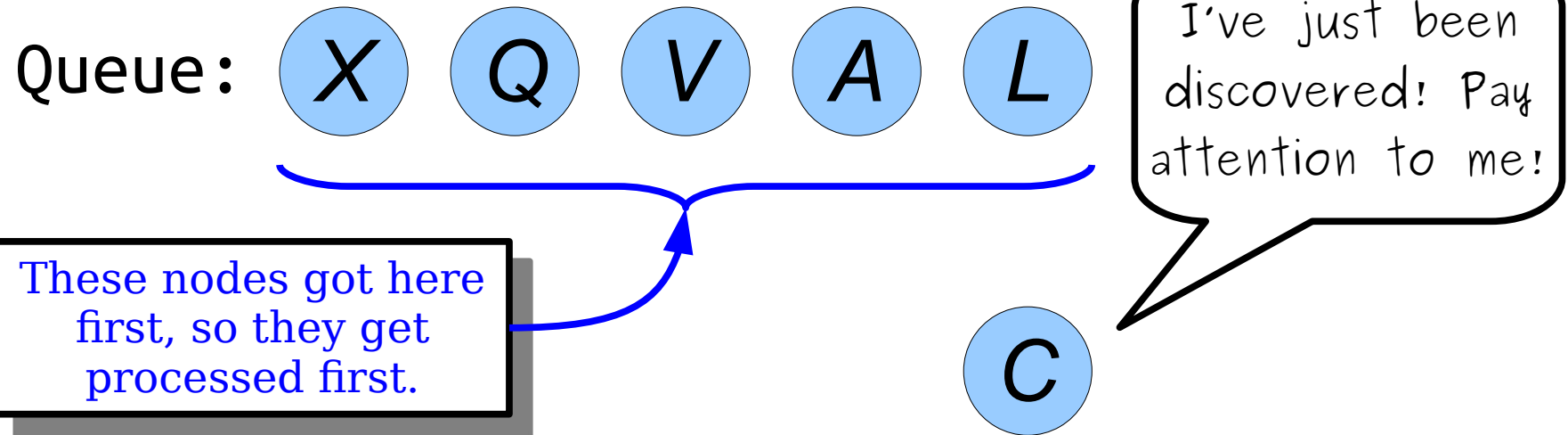
Depth-First Search



Rule: Keep trying new experiences! Always go somewhere new if you can, and only back up if there's nothing new to see.

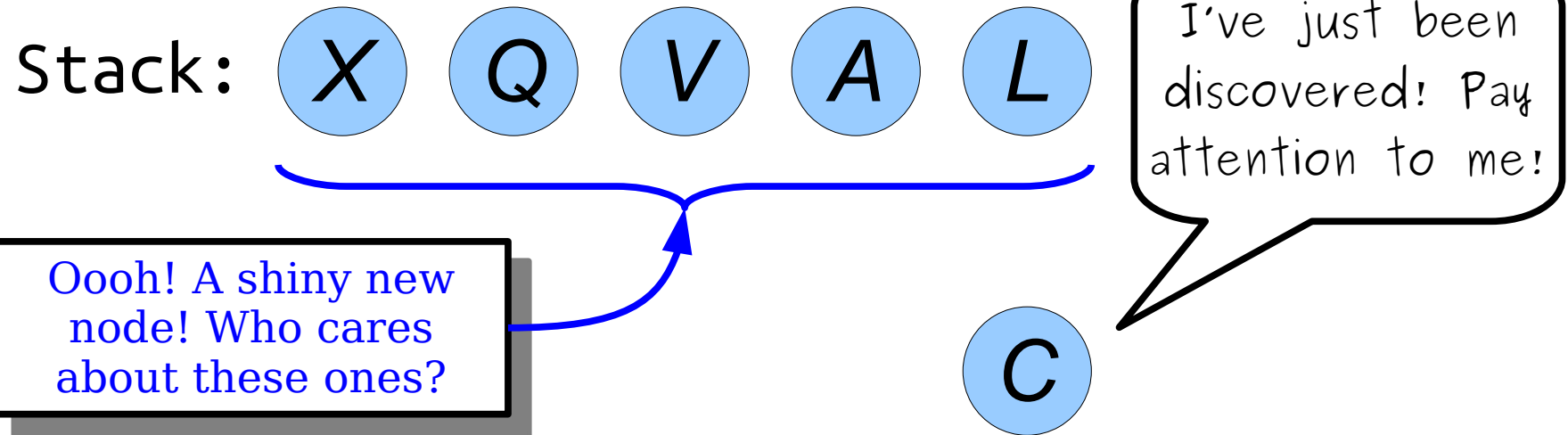
How can we implement this?

Breadth-First Search



```
bfs-from(node v) {  
  make a queue of nodes, initially seeded with v.  
  while the queue isn't empty:  
    dequeue a node curr.  
    process the node curr.  
    for each node adjacent to curr:  
      if that node has never been enqueued:  
        enqueue that node.  
}
```

Depth-First Search



```
dfs-from(node v) {  
  make a stack of nodes, initially seeded with v.  
  while the stack isn't empty:  
    pop a node curr.  
    process the node curr.  
    for each node adjacent to curr:  
      if that node has never been pushed:  
        push that node.  
}
```

For Comparison

```
bfs-from(node v) {  
    make a queue of nodes, initially seeded with v.  
    while the queue isn't empty:  
        dequeue a node curr.  
        process the node curr.  
        for each node adjacent to curr:  
            if that node has never been enqueued:  
                enqueue that node.  
}
```

For Comparison

```
dfs-from(node v) {  
    make a stack of nodes, initially seeded with v.  
    while the stack isn't empty:  
        pop a node curr.  
        process the node curr.  
        for each node adjacent to curr:  
            if that node has never been pushed:  
                push that node.  
}
```

```
dfs-from(node v) {  
    if this is first time we've called dfs-from(v):  
        process node v  
        for each node adjacent to v:  
            call dfs-from on that node  
}
```

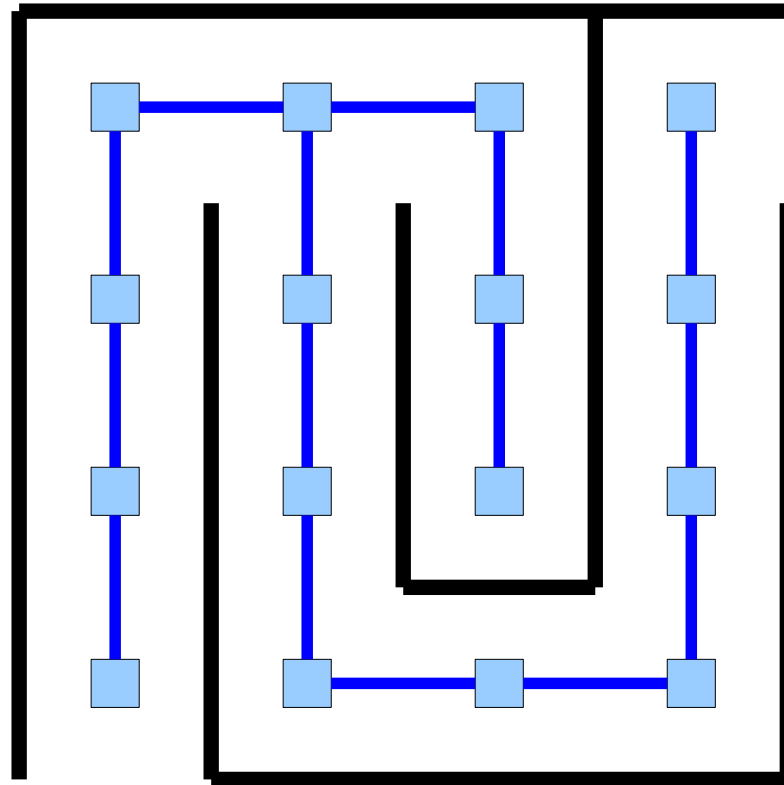
When you see a stack-based algorithm,
think recursion!

BFS and DFS

- Running BFS or DFS from a node in a graph will visit the same set of nodes, but probably in a different order.
- BFS will visit nodes in increasing order of distance.
- DFS does visit nodes in *some* interesting order, but not order of distance.
 - Take CS161 for more details!

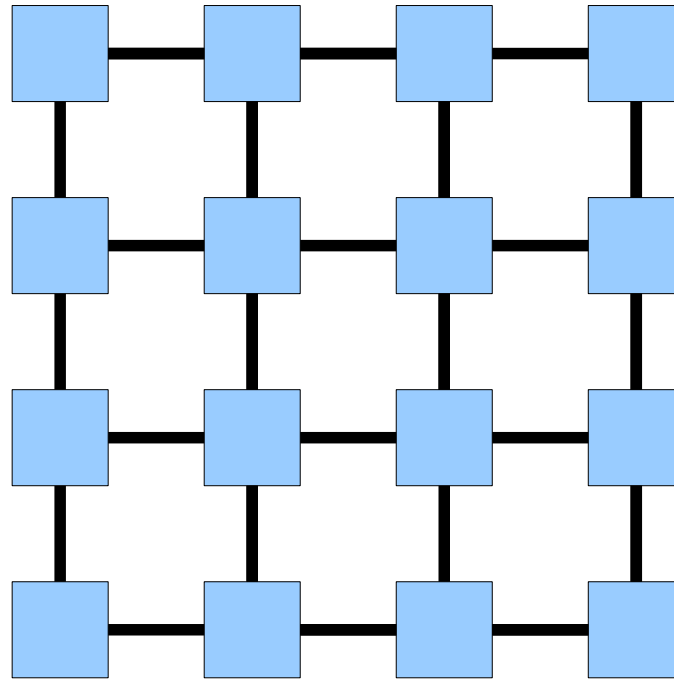
A Whimsical Application

Mazes as Graphs



Creating a Maze with DFS

- Create a *grid graph* of the appropriate size.



- Starting at any node, run a depth-first search, choosing neighbor orderings at random.
- The resulting DFS tree is a maze with one solution.

Next Time

- ***Minimum Spanning Trees***
 - How to wire an electrical grid cheaply.
- ***Applications of MSTs***
 - Data clustering, computational biology, and more!