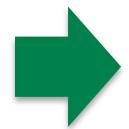


CS 10: Problem solving via Object Oriented Programming

Relationships

Agenda

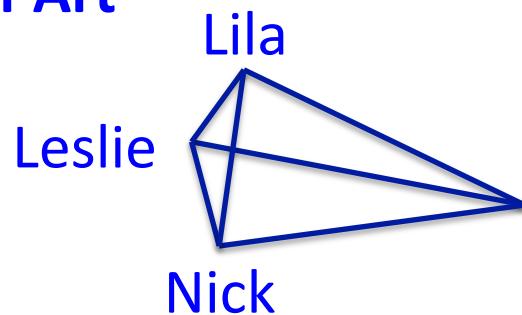


1. Graphs
2. Four common representations
3. Implementation

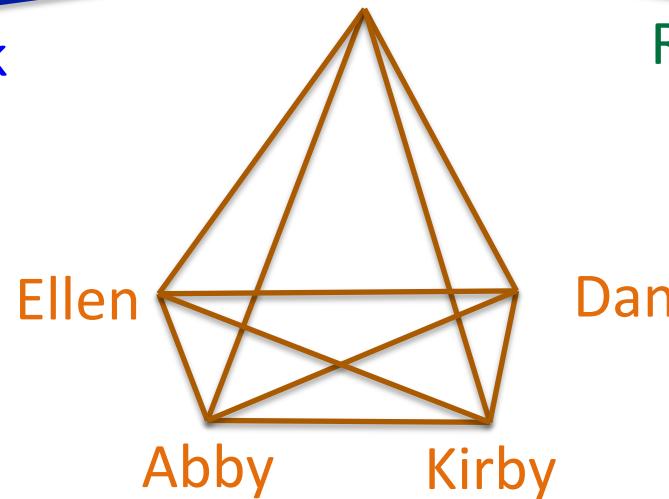
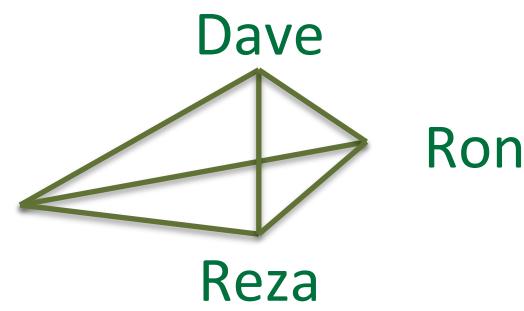
Graphs are a useful way to represent relationships between Objects

My coworkers

The Metropolitan
Museum of Art



Dartmouth

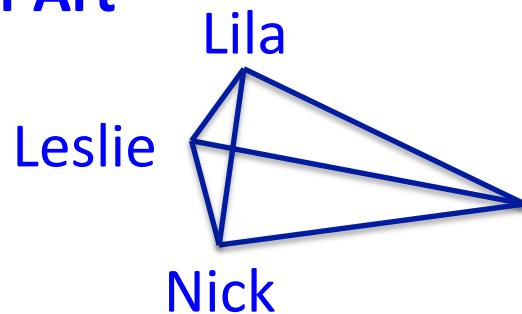


Start up

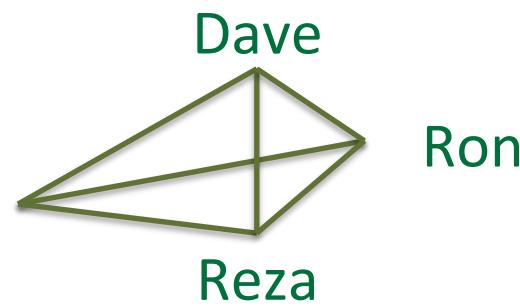
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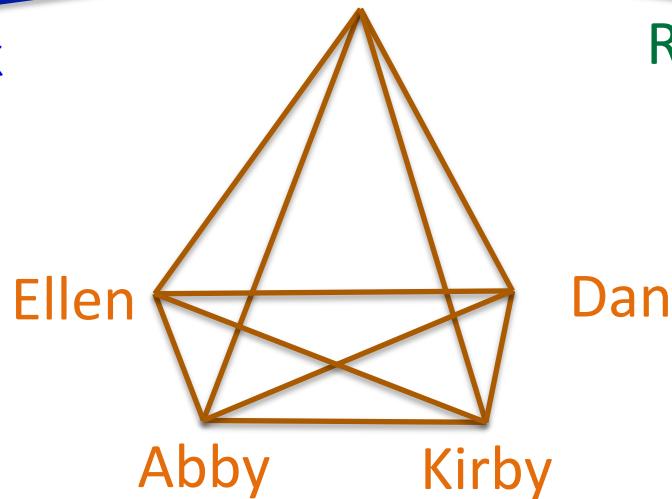
The Metropolitan
Museum of Art



Dartmouth



- I know everyone

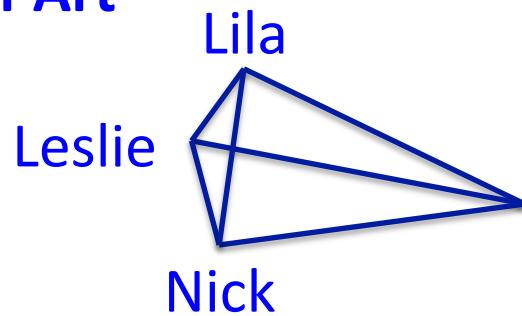


Start up

Graphs are a useful way to represent relationships between Objects

My coworkers

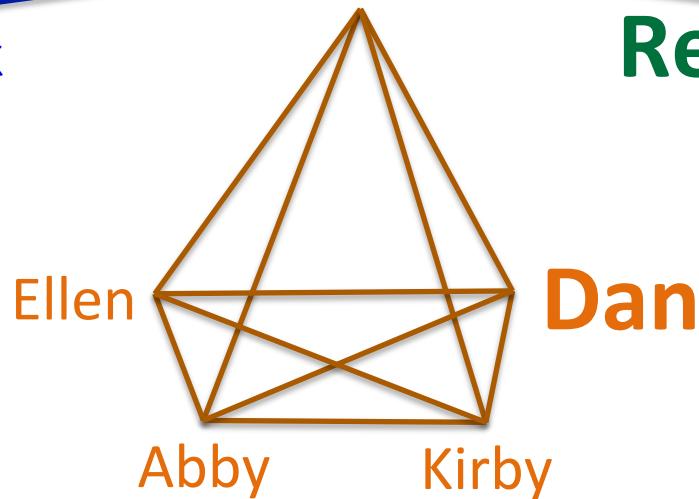
The Metropolitan
Museum of Art



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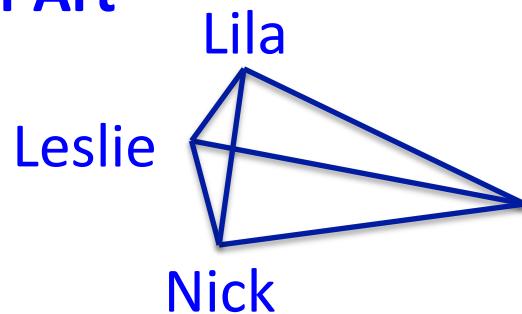
- I know everyone
- Reza and Dan do not know each other directly



Graphs are a useful way to represent relationships between Objects

My coworkers

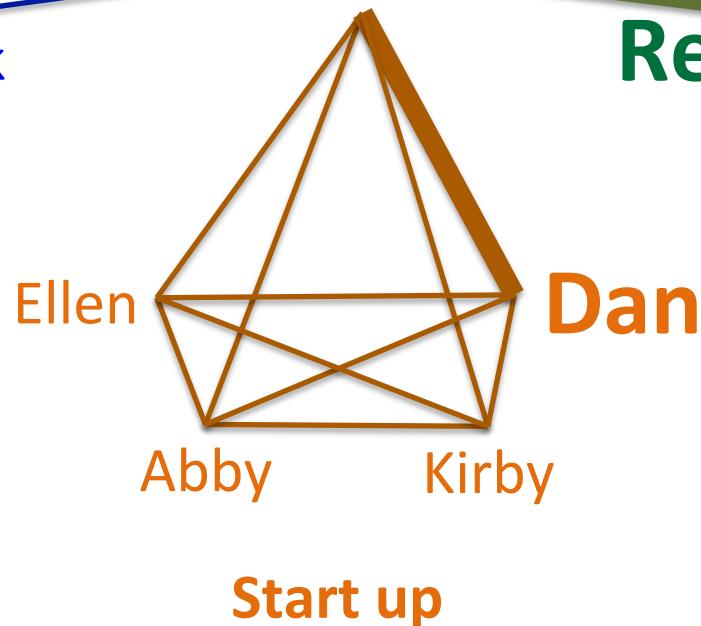
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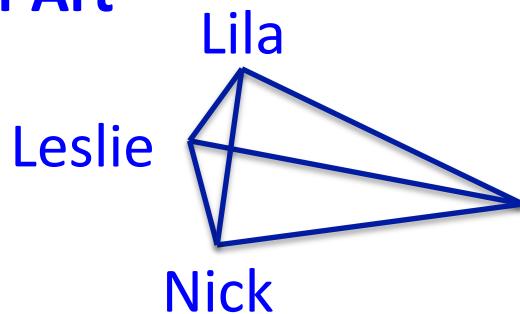
- I know everyone
- Reza and Dan do not know each other directly
- But I could introduce them (there is a path)



Graphs are a useful way to represent relationships between Objects

My coworkers

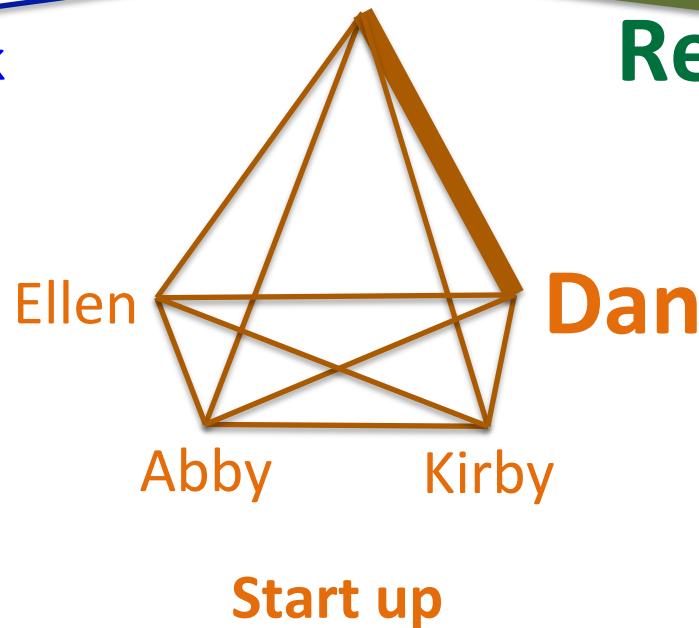
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- I know everyone
- Reza and Dan do not know each other directly
- But I could introduce them (there is a **path**)



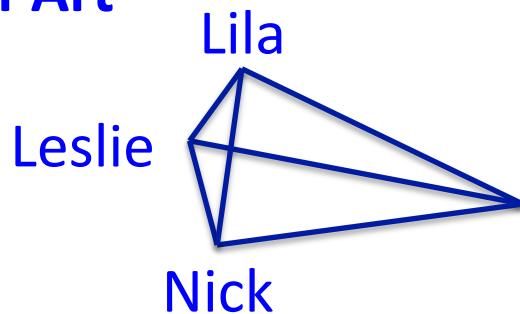
- Nodes are said to be **reachable** if there is a path between them
- There may be nodes that are unreachable

Graphs are a useful way to represent relationships between Objects

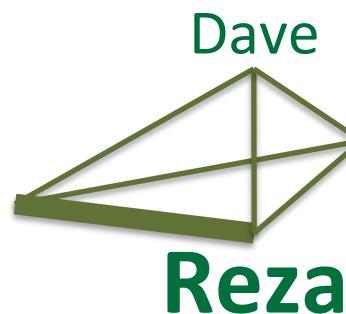
My coworkers



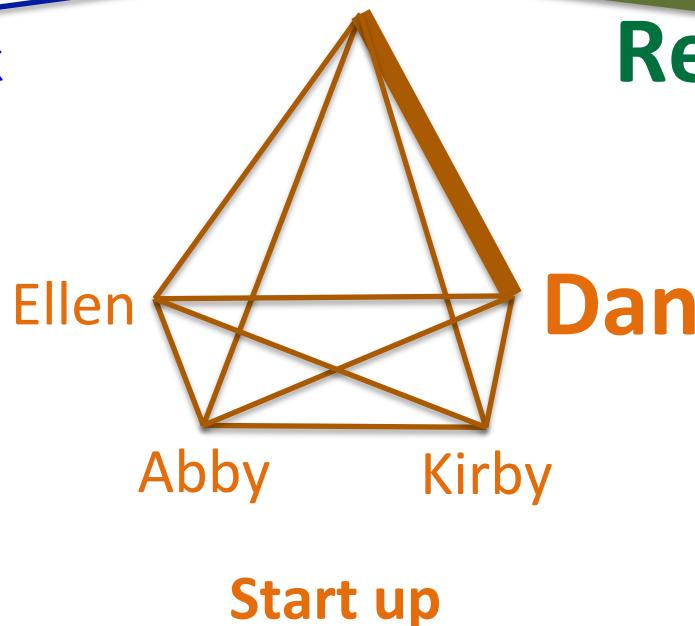
The Metropolitan
Museum of Art



Dartmouth

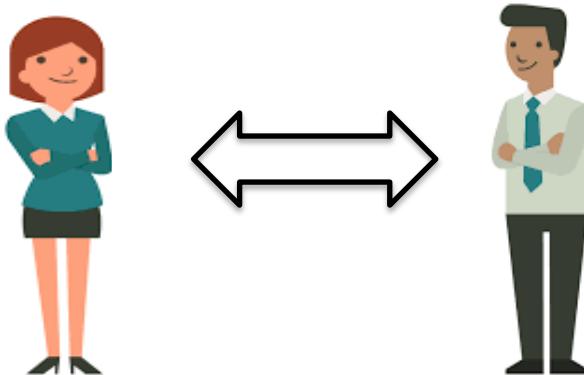


- I know everyone
- Reza and Dan do not know each other directly
- But I could introduce them (there is a path)

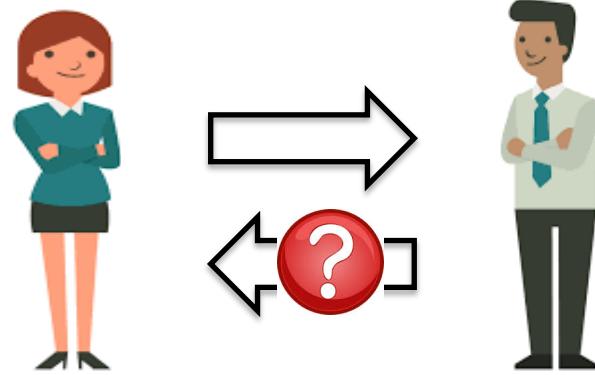


- Nodes are said to be **reachable** if there is a path between them
- There may be nodes that are unreachable

Two types of relationships: Undirected and directed



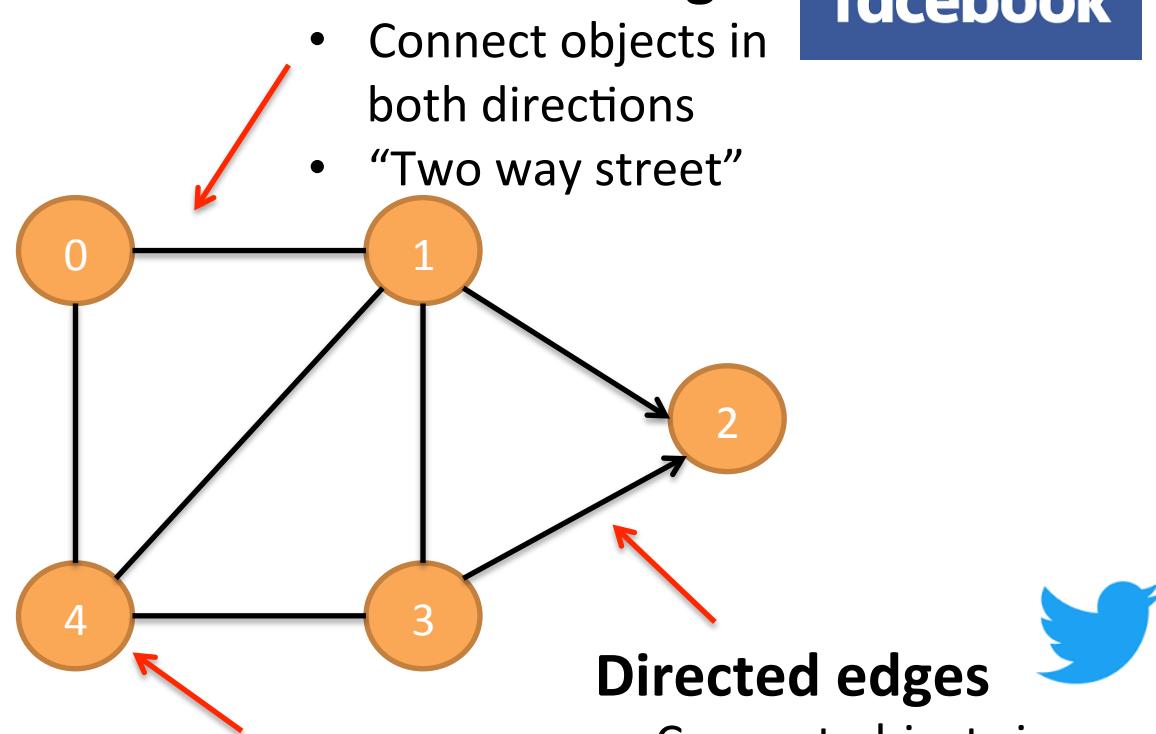
Undirected (Symmetrical)
If Alice is friends with Bob,
then Bob is friends with
Alice



Directed (Asymmetrical)
If Alice follows Bob, then
Bob does not necessarily
follow Alice

Graphs represent directed or undirected relationships with nodes and edges

Graphs



Nodes (vertices)

- Represent objects
- Could be a person or city or computer or intersection of roads...

facebook

Undirected graph
Only undirected edges

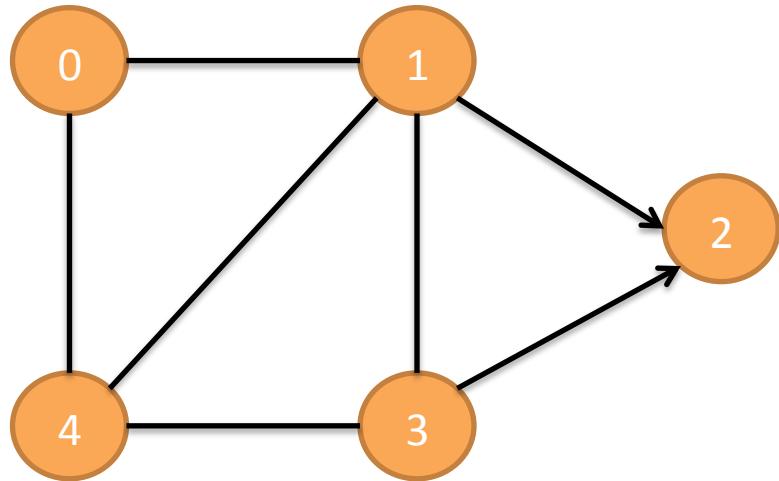
Directed graph
Only directed edges



Mixed graph
Has both directed and undirected edges

Both nodes and edges can hold information about the relationship

Graphs



Nodes

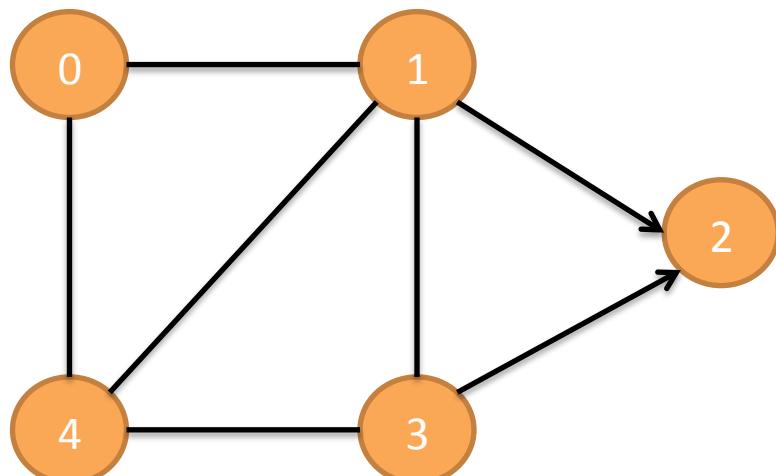
- Represent an Object
- Can be as simple as a String
- Could be more complex like an Object from a Person Class

Edges

- Can hold information about relationship
 - Distance between cities
 - Capacity of a pipe
 - Label of relationship type (“follower”, “friend”, “co-worker”)

Graph ADT defines several useful methods

Graph.java



Create/alter graph

`insertVertex(v)`

Add node v to graph

`insertDirected(u, v) / Undirected(u, v)`

Add edge to graph between node u and node v

`removeVertex(v) / removeDirected(u, v) / removeUndirected(u, v)`

Remove node v or edge from u to v

Traverse graph

`outDegree(v) / inDegree(v)`

Count of edges out of or into node v

`outNeighbors(v) / inNeighbors(v)`

Other nodes connected from/to node v

`hasEdge(u, v)`

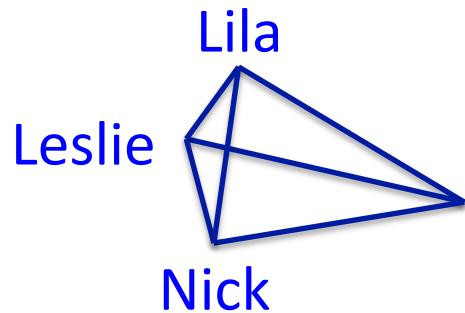
True if node v connected to node u

`getLabel(u, v)`

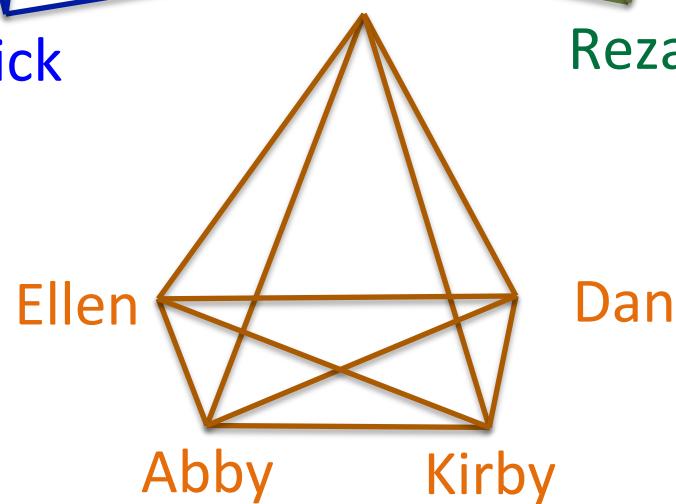
Return label on edge from node u to node v

We can use Graph ADT methods to answer interesting questions

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Start up

Questions we can answer

- Who is the most connected? (most in edges)
- Who are mutual acquaintances (“cliques” where all nodes have edges to each other)
- Who is a friend-of-a-friend but is not yet a friend? (breadth-first search, next class)

Agenda

1. Graphs
2. Four common representations
3. Implementation

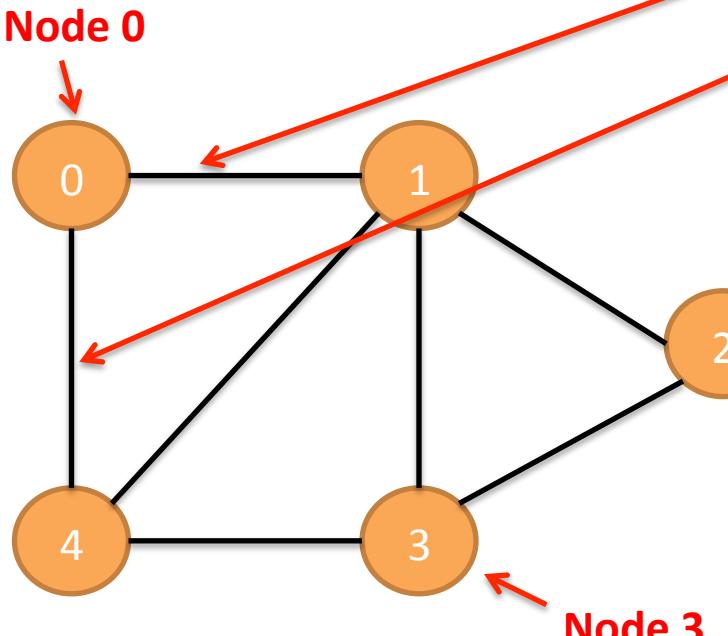
Graphs are commonly represented in one of four different ways

Common Graph representations

- 
1. Edge List
 2. Adjacency List
 3. Adjacency Matrix
 4. Adjacency Map

Edge Lists create an unordered list of vertex pairs where each entry is an edge

1. Edge List List of edges



Assume:

n nodes (here 5)

m edges (here 7)

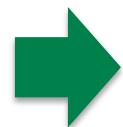
Notes:

- Number nodes 0..n-1
- Edge List stores pairs of indexes that reference nodes
- Each Edge List entry represents an edge between two nodes
- m total entries in Edge List
- Can be ordered to show directed edges
- Insert edge fast, just add to list
- Everything else slow
- Example: `removeVertex` is O(m), have to remove all edges to/from node, so search all edges leading to or from node

Graphs are commonly represented in one of four different ways

Common Graph representations

1. Edge List



2. Adjacency List

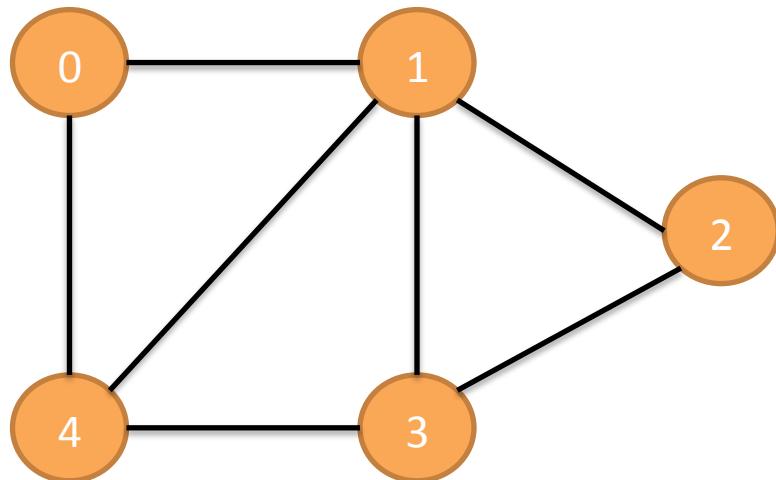
3. Adjacency Matrix

4. Adjacency Map

Adjacency Lists store adjacent nodes in a List; gives improved performance

2. Adjacency List

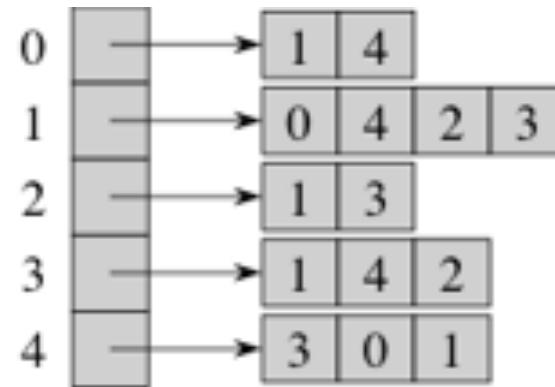
List of Lists



Assume:

n nodes (here 5)

m edges (here 7)



Notes:

- Two vertices are said to be *adjacent* if there is an edge between them
- Store List of nodes in or out of each vertex (same if undirected)
- Might keep two lists, one for in neighbors and one for out neighbors
- Faster to get neighbors than Edge List, just iterate in $O(\text{degree}(v))$ vs. $O(m)$

Graphs are commonly represented in one of four different ways

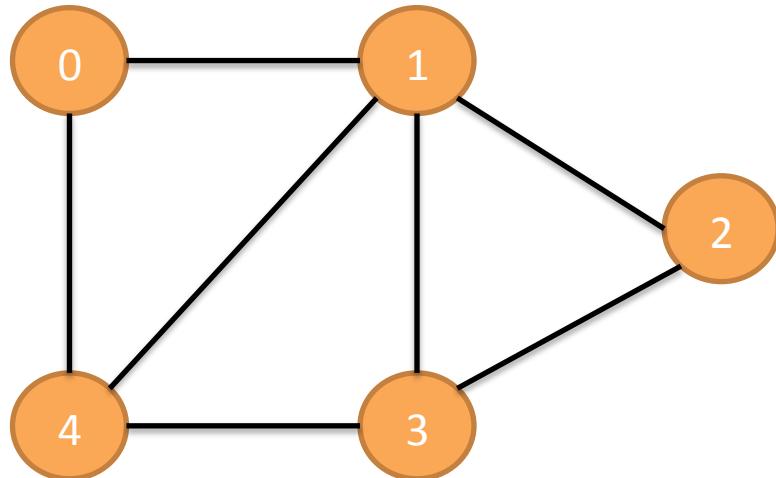
Common Graph representations

1. Edge List
2. Adjacency List
3. Adjacency Matrix
4. Adjacency Map



Adjacency Matrices create an $n \times n$ array to indicate existence of edges

3. Adjacency Matrix $n \times n$ array



Assume:

n nodes (here 5)

m edges (here 7)

	To				
From	0	1	2	3	4
0	0	1	0	0	1
1	1	0	1	1	1
2	0	1	0	1	0
3	0	1	1	0	1
4	1	1	0	1	0

Notes:

- Create $n \times n$ matrix A , set $A[i,j] = 1$ if edge from node i to node j , else 0
- Works if no parallel edges
- Undirected graph $A[i,j] == A[j,i]$
- `hasEdge(u, v)` is now $O(1)$, whereas in Adjacency List it was $O(\text{degree}(u))$
- Finding neighbors now $O(n)$ because have to check entire row or column
- Adding/removing vertices $O(n^2)$, have to rebuild entire matrix

Graphs are commonly represented in one of four different ways

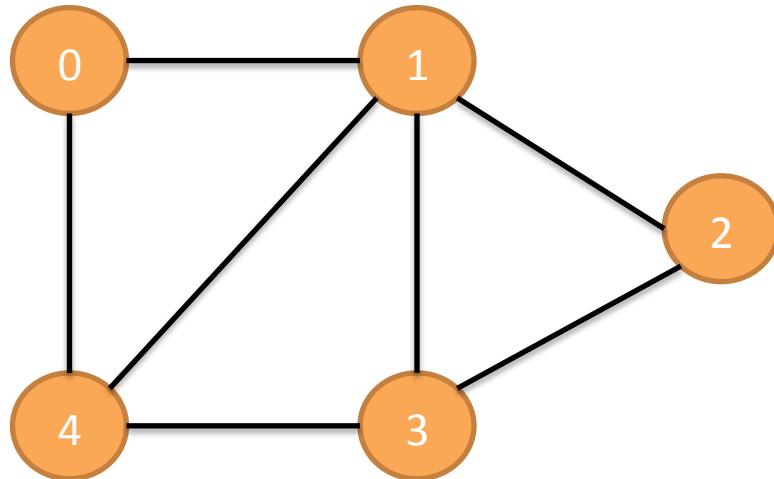
Common Graph representations

1. Edge List
2. Adjacency List
3. Adjacency Matrix
4. Adjacency Map



Adjacency Maps create a Map for each node and a second Map to adjacent nodes

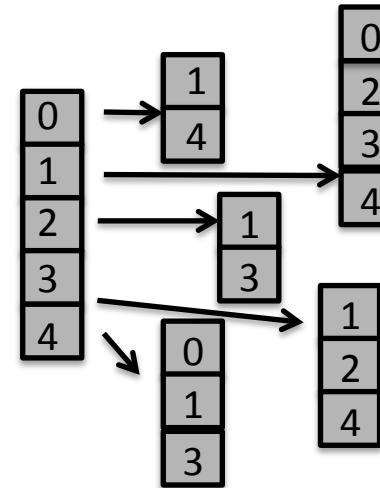
4. Adjacency Map Map of Maps



Assume:

n nodes (here 5)

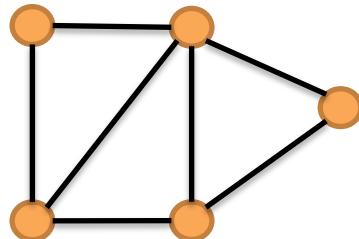
m edges (here 7)



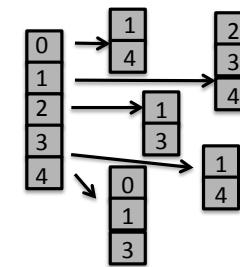
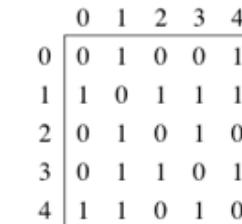
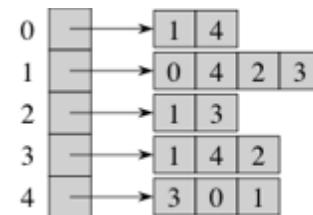
Notes:

- Create Map with vertex names as Key
- Map Value is a second Map of adjacent vertices with vertex name as Key
- Value in second Map is edge label
- No need to number nodes in order
- `hasEdge(u, v)` now expected O(1)
 - Look up u in Map O(1)
 - Look up v in second Map O(1)

How a Graph is implemented has a big impact on run-time performance



```
{ {0,1},  
{0,4}, {1,2},  
{1,3}, {1,4},  
{2,3}, {3,4} }
```



Method	Edge List	Adjacency List	Adjacency Matrix	Adjacency Map
in/ outDegree (v)	O(m)	O(1)	O(n)	O(1)
in/ outNeighbors (v)	O(m)	O(d_v)	O(n)	O(d_v)
hasEdge (u, v)	O(m)	O(min(d_u, d_v))	O(1)	O(1)
insertVertex (v)	O(1)	O(1)	O(n^2)	O(1)
removeVertex (v)	O(m)	O(d_v)	O(n^2)	O(d_v)
insertEdge (u, v, e)	O(1)	O(1)	O(1)	O(1)
removeEdge (u, v)	O(m)	O(1)	O(1)	O(1)

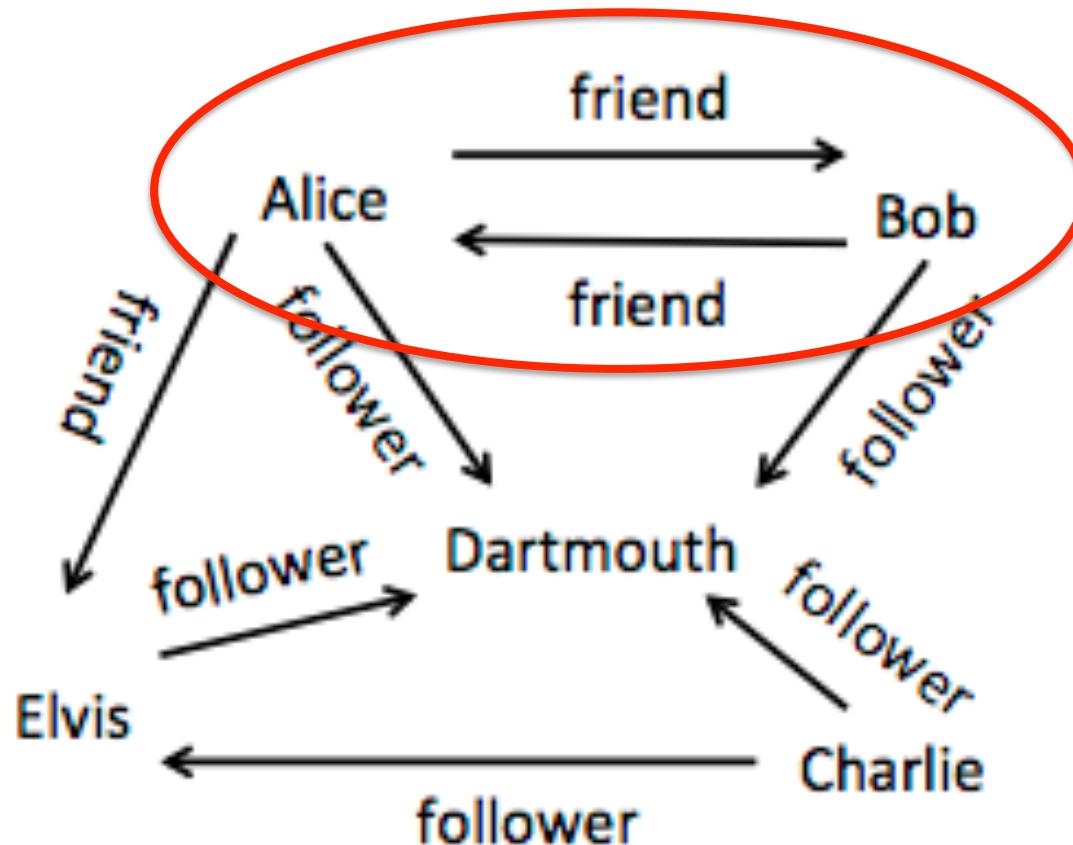
n = number of nodes (5), m = number of edges (7), d_v = degree of node v

Agenda

1. Graphs
2. Four common representations
3. Implementation



Our implementation will allow a mixed graph (directed and undirected edges)



Undirected edges
are two directed
edges, one in each
direction

AdjancyMapGraph.java tracks *in* and *out* edges in two different Maps

AdjacencyMapGraph.java

```
12 public class AdjacencyMapGraph<V, E> implements Graph<V, E> {  
13     protected Map<V, Map<V, E>> out;      // from v1 to v2: { v1 -> { v2 -> edge } }  
14     protected Map<V, Map<V, E>> in;       // to v1 from v2: { v1 -> { v2 -> edge } }  
15  
16     /**  
17      * Default constructor, creating an empty graph  
18      */  
19     public AdjacencyMapGraph() {  
20         in = new HashMap<V, Map<V, E>>();  
21         out = new HashMap<V, Map<V, E>>();  
22     }  
23 }
```

Will normally declare something like:

```
Graph<String, String> relationships = new AdjacencyMapGraph<String, String>();
```

Vertices V will be Strings (e.g., someone's name)

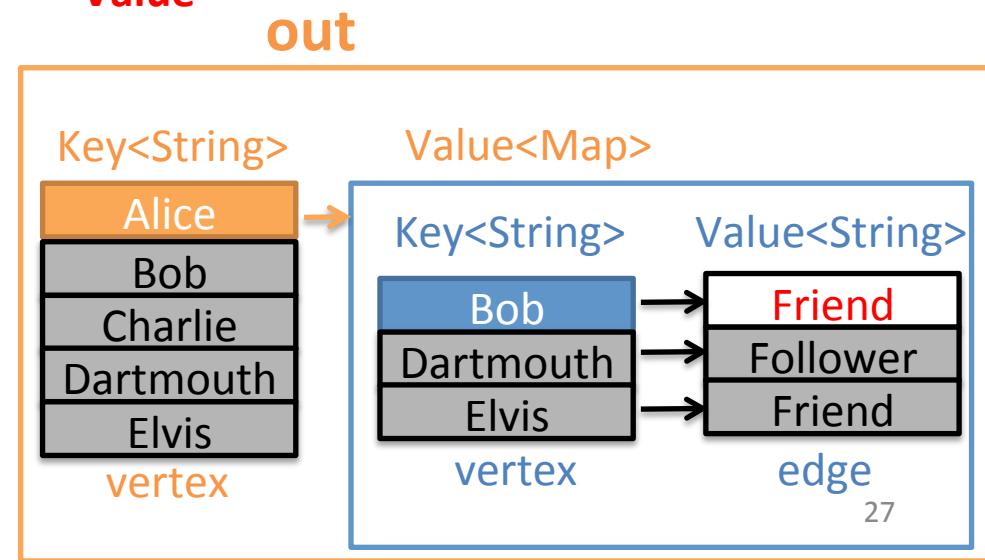
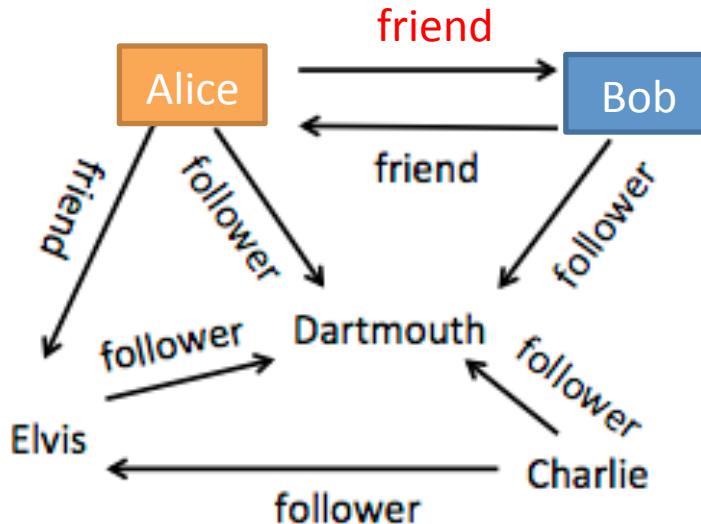
Edges E will be Strings (e.g., "follows" or "friend")

out tracks edges leaving a vertex

AdjacencyMapGraph.java

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12 public class AdjacencyMapGraph<V, E> implements Graph<V, E> {  
13     protected Map<V, Map<V, E>> out;      // from v1 to v2: { v1 -> { v2 -> edge } }  
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21         out = new HashMap<V, Map<V, E>>();  
22     }  
23 }
```

- ***out* tracks edges leaving a vertex**
- ***out* is a Map with vertex as Key, Map as Value**
- **Value Map has end vertex as Key, Edge as Value**

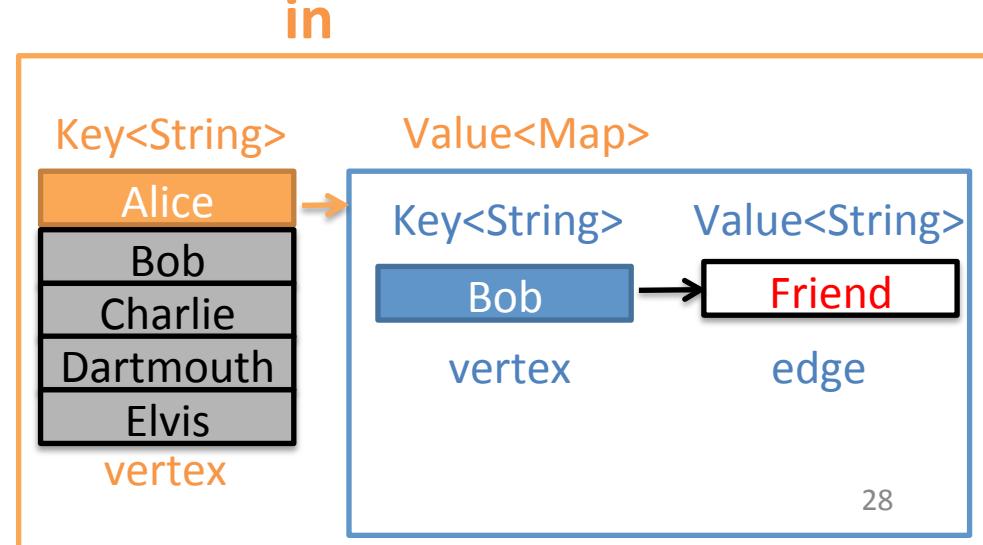
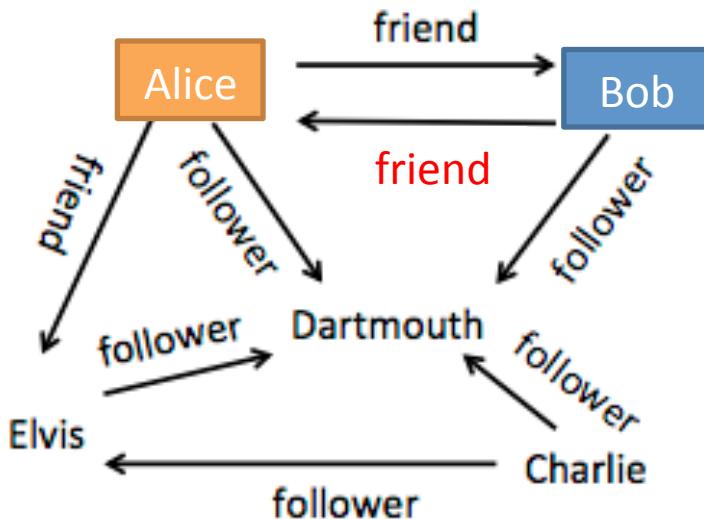


in tracks edges entering a vertex

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21         out = new HashMap<V, Map<V, E>>();  
22     }  
23 }
```

- *in* tracks edges entering a vertex
- *in* is a Map with vertex as Key, Map as Value
- Value Map has start vertex as Key, Edge as Value



Inserting vertices and edges requires updating both *in* and *out*

AdjacencyMapGraph.java

```
bb  
67  public void insertVertex(V v) {  
68      if (!out.keySet().contains(v)) {  
69          out.put(v, new HashMap<V, E>()); // edges from v  
70          in.put(v, new HashMap<V, E>());    // edges to v  
71      }  
72  }  
73  
74  public void insertDirected(V u, V v, E e) {  
75      out.get(u).put(v, e); //out from u to v  
76      in.get(v).put(u, e); //reversed for in, from v to u  
77  }  
78  
79  public void insertUndirected(V u, V v, E e) {  
80      // insert in both directions  
81      insertDirected(u, v, e);  
82      insertDirected(v, u, e);  
83  }
```

- Adding new vertex adds Key to both *in* and *out*
- Value in both cases is set to empty Map



Add directed edge from vertex u to v with edge label e

- Get *out* Value Map using vertex u as Key

Inserting vertices and edges requires updating both *in* and *out*

AdjacencyMapGraph.java

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bb  
67  public void insertVertex(V v) {  
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```



- Adding new vertex adds Key to both *in* and *out*
- Value in both cases is set to empty Map

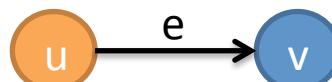
Add directed edge from vertex u to v with edge label e

- Get *out* Value Map using vertex u as Key
- Put new entry into Value Map with destination vertex v and edge e

Inserting vertices and edges requires updating both *in* and *out*

AdjacencyMapGraph.java

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bb  
67  public void insertVertex(V v) {  
68      if (!out.keySet().contains(v)) {  
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```



- Adding new vertex adds Key to both *in* and *out*
- Value in both cases is set to empty Map

Add directed edge from vertex u to v with edge label e

- Get *out* Value Map using vertex u as Key
- Put new entry into Value Map with destination vertex v and edge e
- Repeat process, updating *in* for incoming edge e from v to u

We model undirected edges as directed edges going in both directions

AdjacencyMapGraph.java

```
bb
67  public void insertVertex(V v) {
68      if (!out.keySet().contains(v)) {
69          out.put(v, new HashMap<V, E>()); // edges from v
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74  public void insertDirected(V u, V v, E e) {
75      out.get(u).put(v, e); //out from u to v
76      in.get(v).put(u, e); //reversed for in, from v to u
77  }
78
79  public void insertUndirected(V u, V v, E e) {
80      // insert in both directions
81      insertDirected(u, v, e); ←
82      insertDirected(v, u, e);
83  }
```

Adding undirected edge creates two directed edges

- One edge from u to v
- One edge from v to u

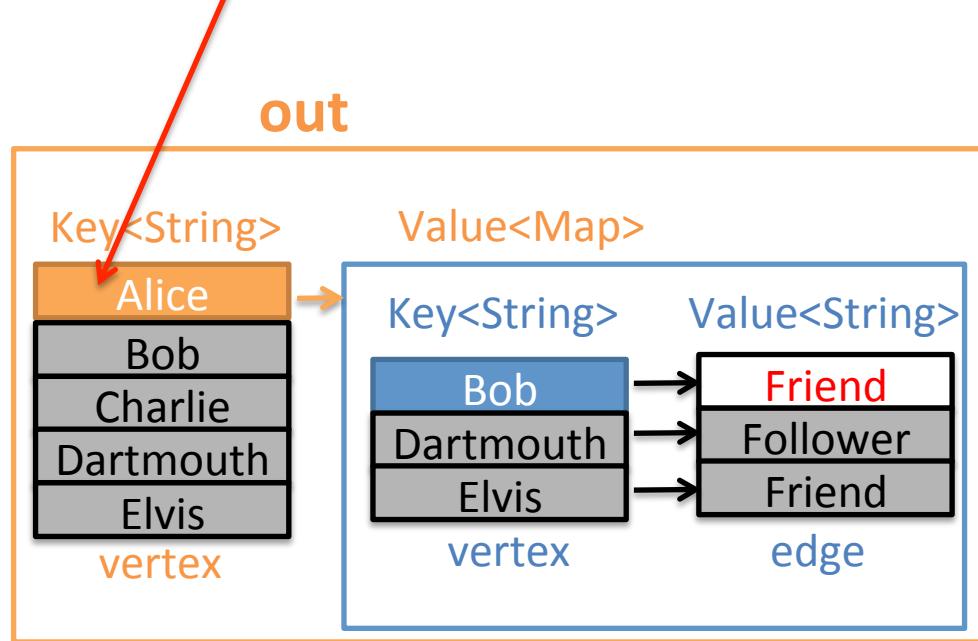
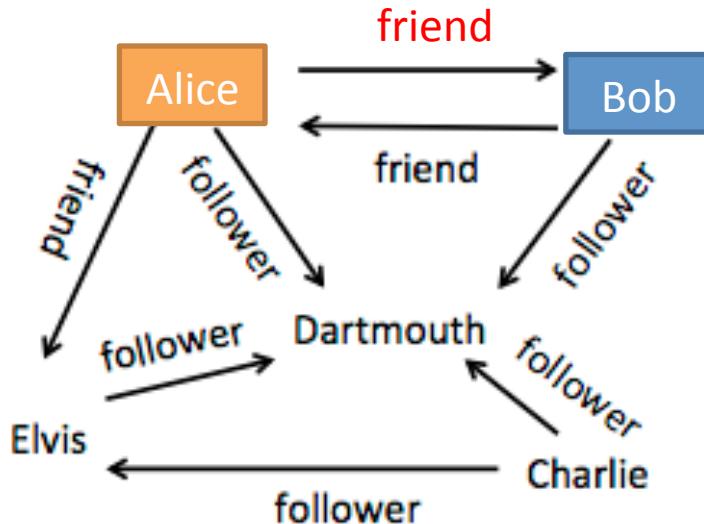


$getLabel(u,v)$ returns the label on the edge between u and v

AdjacencyMapGraph.java

```
62  
63     public E getLabel(V u, V v) {  
64         return out.get(u).get(v);  
65     }  
66 }
```

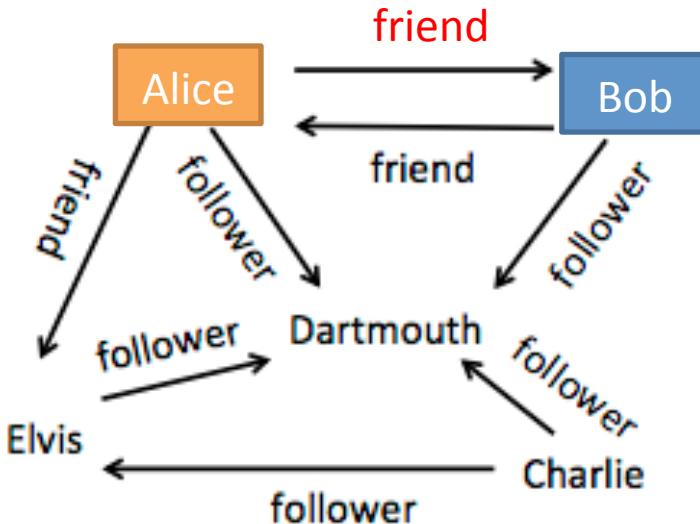
- $getLabel(u,v)$ returns label on edge from u to v
- $getLabel("Alice", "Bob")$ returns "Friend"
- First get Value Map for Key "Alice" from out



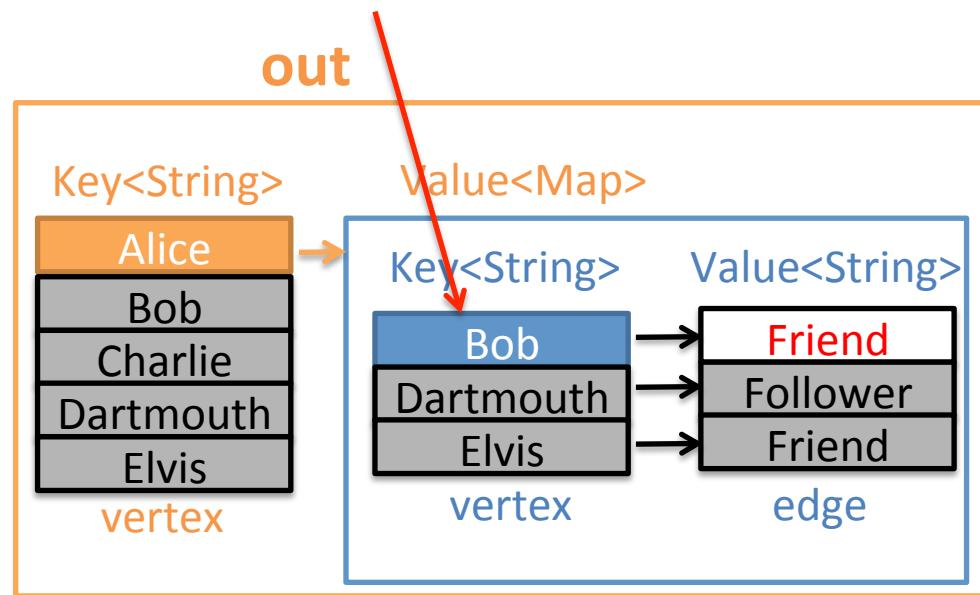
$getLabel(u,v)$ returns the label on the edge between u and v

AdjacencyMapGraph.java

```
62  
63     public E getLabel(V u, V v) {  
64         return out.get(u).get(v);  
65     }  
66 }
```



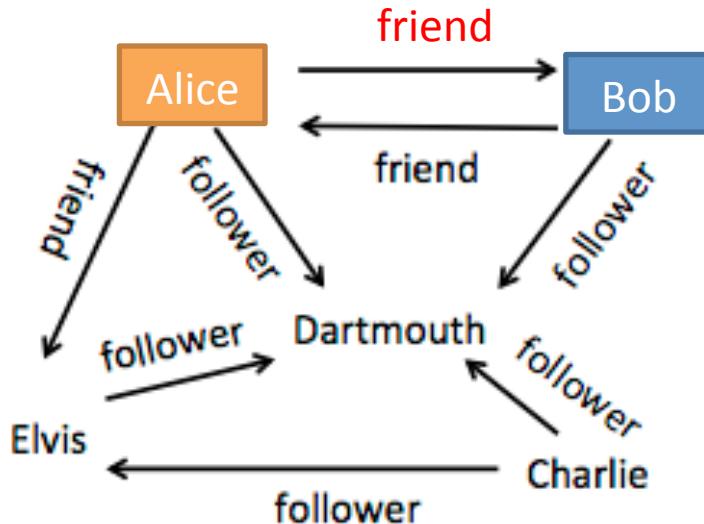
- $getLabel(u,v)$ returns label on edge from u to v
- $getLabel("Alice", "Bob")$ returns "Friend"
- First get Value Map for Key "Alice" from out
- Next get use Key "Bob" to get Value String



$getLabel(u,v)$ returns the label on the edge between u and v

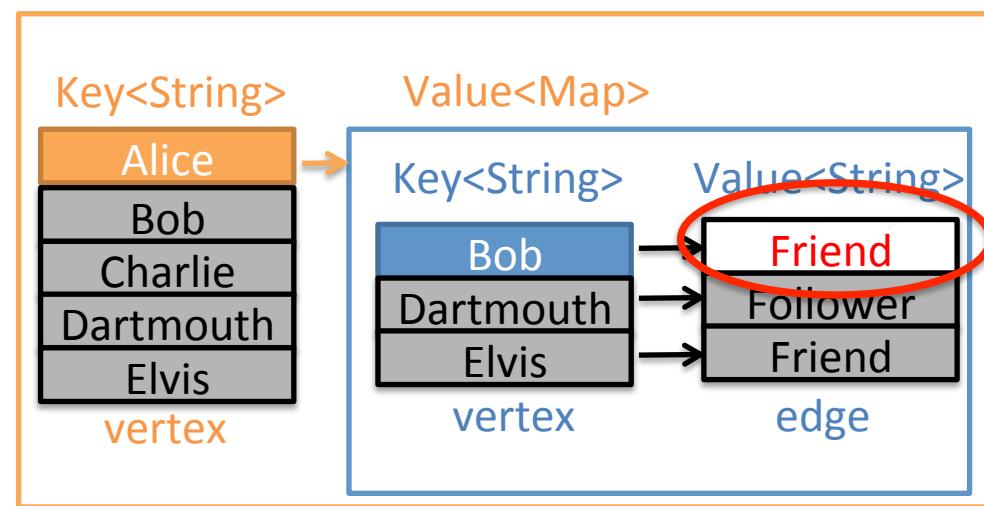
AdjacencyMapGraph.java

```
62  
63     public E getLabel(V u, V v) {  
64         return out.get(u).get(v);  
65     }  
66 }
```



- $getLabel(u,v)$ returns label on edge from u to v
- $getLabel("Alice", "Bob")$ returns “Friend”
- First get Value Map for Key “Alice” from out
- Next get use Key “Bob” to get Value String
- Return “Friend”

out



When removing edges and vertices, must remove from both *in* and *out* Maps

AdjacencyMapGraph.java

```
 85 public void removeVertex(V v) {  
 86     if (!out.keySet().contains(v)) return;  
 87     //remove all edges to and from v  
 88     // remove all in edges to v  
 89     for (V u : inNeighbors(v)) { // u has an out edge to v  
 90         out.get(u).remove(v);  
 91     }  
 92     //remove all out edges from v  
 93     for (V w : outNeighbors(v)) { // w has an in edge to v  
 94         in.get(w).remove(v);  
 95     }  
 96     //remove node from outer map  
 97     in.remove(v);  
 98     out.remove(v);  
 99 }  
100  
101 public void removeDirected(V u, V v) {  
102     //remove edge from u to v in both in and out maps  
103     in.get(v).remove(u); //remove from in to v  
104     out.get(u).remove(v); //remove from out of u  
105 }  
106  
107 public void removeUndirected(V u, V v) {  
108     // remove in both directions  
109     removeDirected(u, v);  
110     removeDirected(v, u);  
111 }  
112 }
```

Removing vertex *v*

- Remove all *in* edges (out from neighbor)
- Remove all *out* edges (in from neighbor)
- Then remove *v* from *in* and *out* Maps

```
public Iterable<V> outNeighbors(V v) {  
    return out.get(v).keySet();  
}  
  
public Iterable<V> inNeighbors(V v) {  
    return in.get(v).keySet();  
}
```

- Removing directed edge from *u* to *v*
- Remove from both *in* and *out* Maps
- Removing undirected, call *removeDirected()* twice

RelationshipTest.java: create graph with both directed and non-directed edges

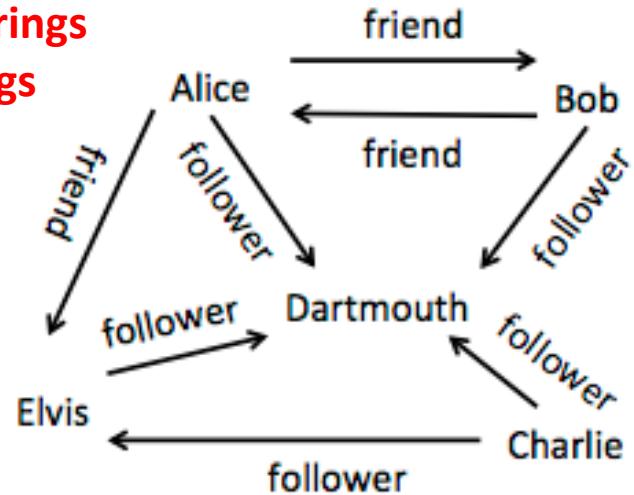
RelationshipTest.java

```
4 public class RelationshipsTest {  
5     public static void main(String[] args) {  
6         Graph<String, String> relationships = new AdjacencyMapGraph<  
7  
8             relationships.insertVertex("Alice");  
9             relationships.insertVertex("Bob"); ← Add nodes  
10            relationships.insertVertex("Charlie");  
11            relationships.insertVertex("Dartmouth");  
12            relationships.insertVertex("Elvis");  
13            relationships.insertDirected("Alice", "Dartmouth", "follower");  
14            relationships.insertDirected("Bob", "Dartmouth", "follower");  
15            relationships.insertDirected("Charlie", "Dartmouth", "follower");  
16            relationships.insertDirected("Elvis", "Dartmouth", "follower");  
17            relationships.insertUndirected("Alice", "Bob", "friend"); // symmetric, undirected edge  
18            relationships.insertDirected("Alice", "Elvis", "friend"); // not symmetric, directed edge  
19            relationships.insertDirected("Charlie", "Elvis", "follower");  
20  
21            System.out.println("The graph:"); ← Add edges  
22            System.out.println(relationships);
```

Declare graph:

Vertices V are Strings

Edges E are Strings



Output (from implicit `toString()` call):

The graph:

Vertices: [Bob, Dartmouth, Alice, Elvis, Charlie]

Out edges: {Bob={Dartmouth=follower, Alice=friend}, Dartmouth={},

Alice={Dartmouth=follower, Bob=friend, Elvis=friend}, Elvis={Dartmouth=follower},

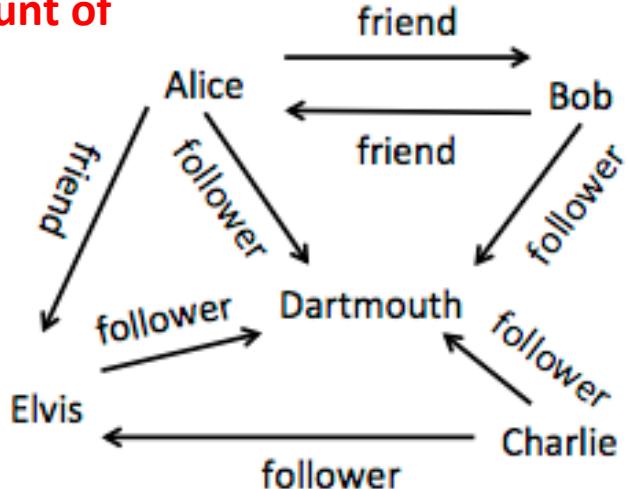
Charlie={Dartmouth=follower, Elvis=follower}}

RelationshipTest.java: create graph with both directed and non-directed edges

RelationshipTest.java

```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:");
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis");
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriended Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```

- *inDegree(u)* gives count of edges coming into u



Output:

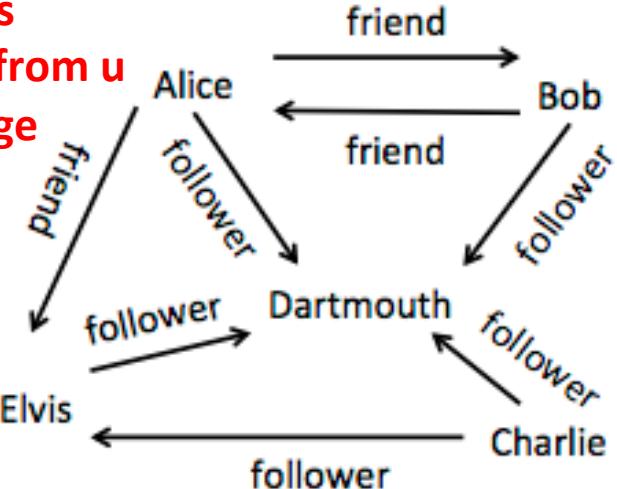
Links to Dartmouth = 4

RelationshipTest.java: create graph with both directed and non-directed edges

RelationshipTest.java

```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:");
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis");
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriended Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```

- *outNeighbors(u)* gives neighboring vertices from u
- *getLabel(u,v)* gets edge label from u to v



Output:

Links from Alice:

Dartmouth (follower)

Bob (friend)

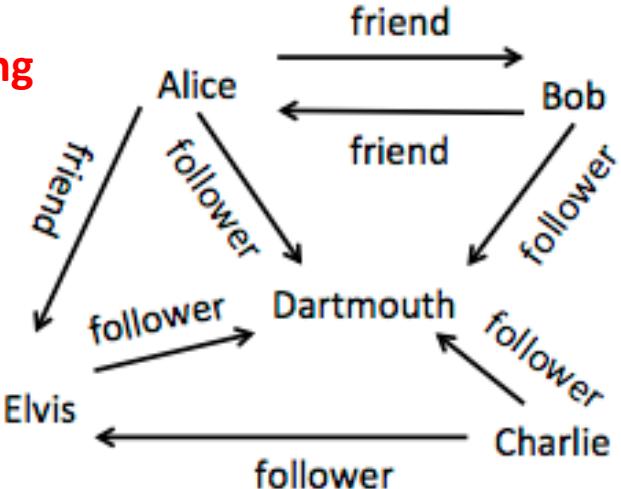
Elvis (friend)

RelationshipTest.java: create graph with both directed and non-directed edges

RelationshipTest.java

```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:")
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis");
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriended Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```

- *inNeighbors(u) gives neighbors on incoming edges*



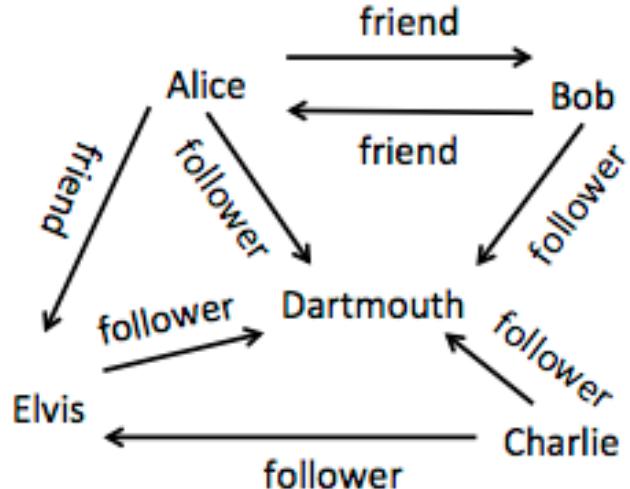
Output:

Links to Dartmouth:
Bob (follower)
Alice (follower)
Elvis (follower)
Charlie (follower)

RelationshipTest.java: create graph with both directed and non-directed edges

RelationshipTest.java

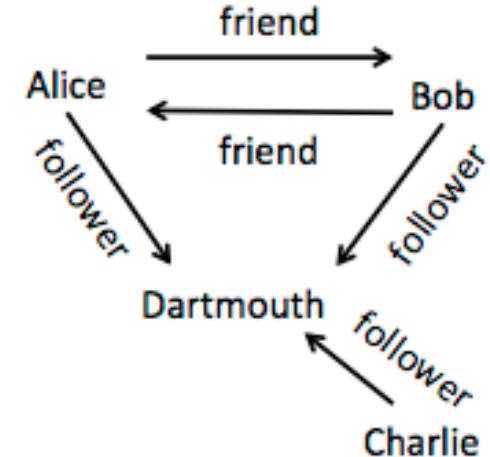
```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:");
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis"); Removing node Elvis  
also removes link from  
Alice and others
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriended Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```



RelationshipTest.java: create graph with both directed and non-directed edges

RelationshipTest.java

```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:");
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis"); Removing node Elvis  
also removes link from  
Alice and others
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriended Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```



Output:

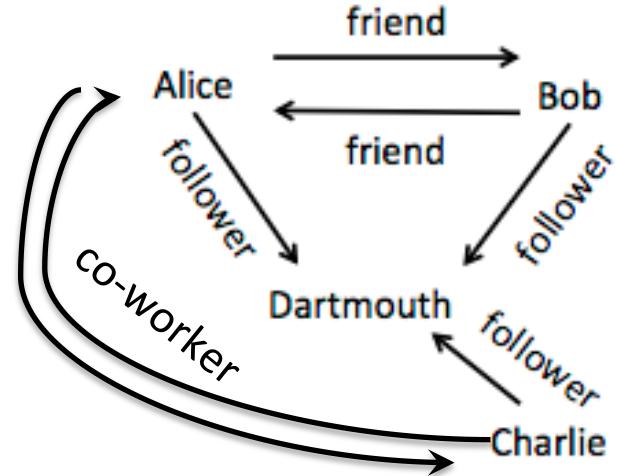
Links from Alice:
Dartmouth (follower)
Bob (friend)

RelationshipTest.java: create graph with both directed and non-directed edges

RelationshipTest.java

```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:");
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis");
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriended Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```

Adding link between
Charlie and Alice



Output:

Alice & Charlie work together

Links from Alice:

Dartmouth (follower)

Bob (friend)

Charlie (co-worker)

Links from Charlie:

Dartmouth (follower)

Alice (co-worker)

RelationshipTest.java: create graph with both directed and non-directed edges

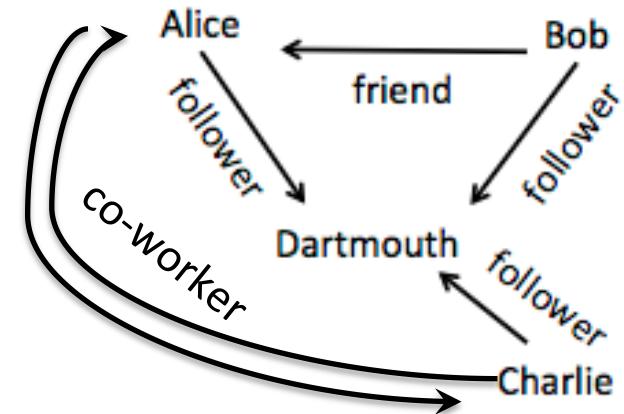
RelationshipTest.java

```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:");
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis");
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriends Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```

Alice removes edge to

Bob

And Charlie no
longer co-
worker



Output:

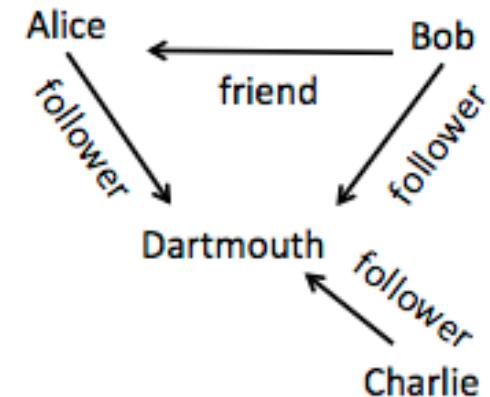
Alice unfriends Bob
and Charlie gets fired

Links from Alice:
Dartmouth (follower)

RelationshipTest.java: create graph with both directed and non-directed edges

RelationshipTest.java

```
21 System.out.println("The graph:");
22 System.out.println(relationships);
23
24 System.out.println("\nLinks to Dartmouth = " + relationships.inDegree("Dartmouth"));
25
26 System.out.println("\nLinks from Alice:");
27 for (String to : relationships.outNeighbors("Alice"))
28     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
29
30 System.out.println("\nLinks to Dartmouth:");
31 for (String from : relationships.inNeighbors("Dartmouth"))
32     System.out.println(from + " ("+relationships.getLabel(from, "Dartmouth")+")");
33
34 System.out.println("\nElvis has left the building");
35 relationships.removeVertex("Elvis");
36 System.out.println("\nLinks from Alice:");
37 for (String to : relationships.outNeighbors("Alice"))
38     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
39
40 System.out.println("\nAlice & Charlie work together");
41 relationships.insertUndirected("Alice", "Charlie", "co-worker");
42 System.out.println("\nLinks from Alice:");
43 for (String to : relationships.outNeighbors("Alice"))
44     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
45 System.out.println("\nLinks from Charlie:");
46 for (String to : relationships.outNeighbors("Charlie"))
47     System.out.println(to + " ("+relationships.getLabel("Charlie", to)+")");
48
49 System.out.println("\nAlice unfriended Bob");
50 relationships.removeDirected("Alice", "Bob");
51 System.out.println("and Charlie gets fired");
52 relationships.removeUndirected("Alice", "Charlie");
53 System.out.println("\nLinks from Alice:");
54 for (String to : relationships.outNeighbors("Alice"))
55     System.out.println(to + " ("+relationships.getLabel("Alice", to)+")");
56
57 System.out.println("\nThe final graph:");
58 System.out.println(relationships);
```



Output:

The final graph:

Vertices: [Bob, Dartmouth, Alice, Charlie]

Out edges: {Bob={Dartmouth=follower, Alice=friend}, Dartmouth={}₄₅

Alice={Dartmouth=follower}, Charlie={Dartmouth=follower}}

