Chapter 29 Weighted Graphs and Applications

Objectives

- To represent weighted edges using adjacency matrices and adjacency lists (§29.2).

- To model weighted graphs using the WeightedGraph class that extends the AbstractGraph class (§29.3).

- To design and implement the algorithm for finding a minimum spanning tree (§29.4).

- To define the MST class that extends the Tree class (§29.4).

- To design and implement the algorithm for finding single-source shortest paths (§29.5).

- To define the ShortestPathTree class that extends the Tree class (§29.5).

- To solve the weighted nine tail problem using the shortest-path algorithm (§29.6).

Weighted Graph Animation

www.cs.armstrong.edu/liang/animation/web/WeightedGraphLearningTool.html

Representing Weighted Graphs

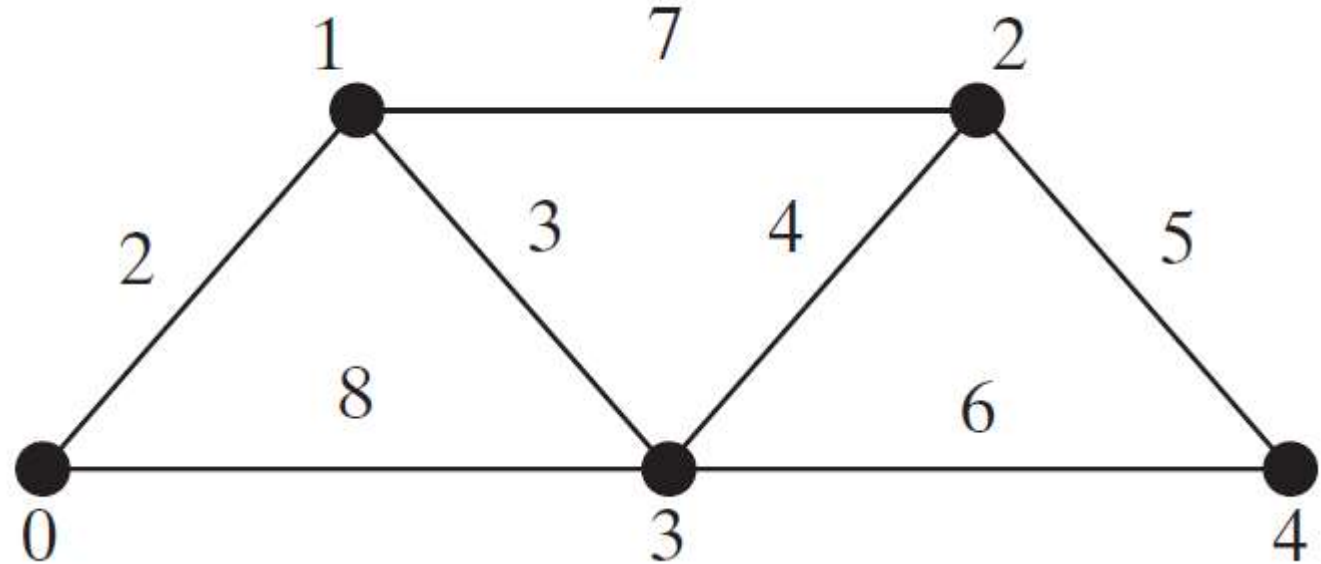Representing Weighted Edges: Edge Array

Weighted Adjacency Matrices

Adjacency Lists

Representing Weighted Edges: Edge Array

int[][] edges = {{0, 1, 2}, {0, 3, 8},
  {1, 0, 2}, {1, 2, 7}, {1, 3, 3},
  {2, 1, 7}, {2, 3, 4}, {2, 4, 5},
  {3, 0, 8}, {3, 1, 3}, {3, 2, 4}, {3, 4, 6},
  {4, 2, 5}, {4, 3, 6}
};

Representing Weighted Edges: Edge Array

```
Integer[][] adjacencyMatrix = {
   {null, 2, null, 8, null },
   {2, null, 7, 3, null },
   {null, 7, null, 4, 5},
   {8, 3, 4, null, 6},
   {null, null, 5, 6, null}
```

	0	1	2	3	4
0	null	2	null	8	null
1	2	null	7	3	null
2	null	7	null	4	5
3	8	3	4	null	6
4	null	null	5	6	null
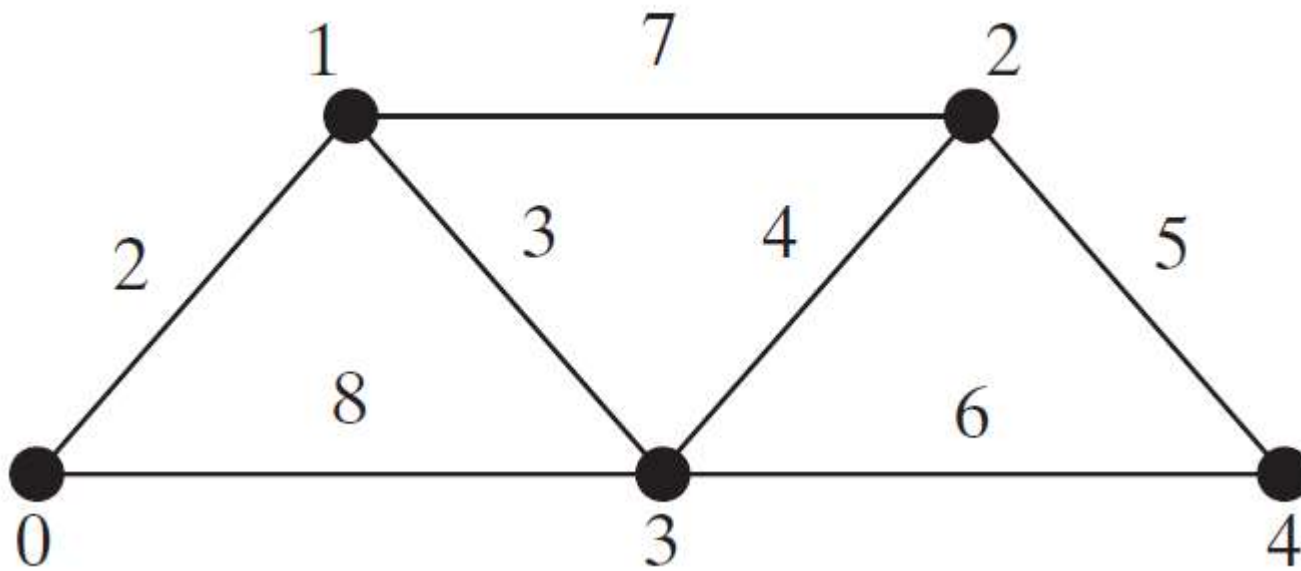
Edge Adjacency Lists

java.util.List<WeightedEdge>[] neighbors = **new** java.util.List[**5**];

neighbors[0]	WeightedEdge(0, 1, 2)	WeightedEdge(0, 3, 8)		
neighbors[1]	WeightedEdge(1, 0, 2)	WeightedEdge(1, 3, 3)	WeightedEdge(1, 2, 7)	
neighbors[2]	WeightedEdge(2, 3, 4)	WeightedEdge(2, 4, 5)	WeightedEdge(2, 1, 7)	
neighbors[3]	WeightedEdge(3, 1, 3)	WeightedEdge(3, 2, 4)	WeightedEdge(3, 4, 6)	WeightedEdge(3, 0, 8)
neighbors[4]	WeightedEdge(4, 2, 5)	WeightedEdge(4, 3, 6)		

WeightedEdge
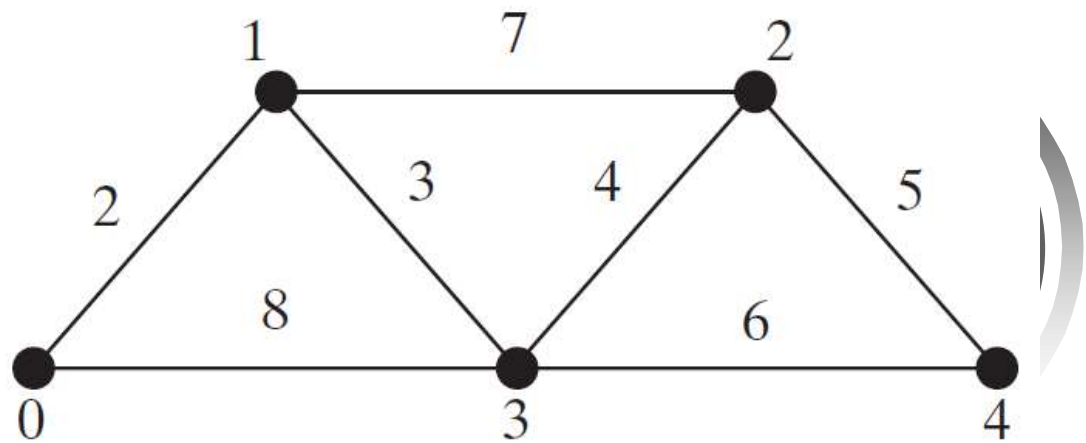
Edge Adjacency Lists

For flexibility, we will use an array list rather than a fixed-sized array to represent **list** as follows:

List<List<WeightedEdge>> list = **new** java.util.ArrayList<>();

```
┌─────────────────────────────────────────────┐
│          UnweigtedGraph<V>                   │      Defined in Figure 28.9.
└─────────────────────────────────────────────┘
                      △
                      │
                      │
┌─────────────────────────────────────────────┐
│            WeightedGraph<V>                  │
├─────────────────────────────────────────────┤
```

+WeightedGraph()   Constructs an empty graph.

+WeightedGraph(vertices: V[], edges: int[][])   Constructs a weighted graph with the specified edges and the
                                                  number of vertices in arrays.

+WeightedGraph(vertices: List<V>, edges: Constructs a weighted graph with the specified edges and the
  List<WeightedEdge>)   number of vertices.

+WeightedGraph(edges: int[][],   Constructs a weighted graph with the specified edges in an array
  numberOfVertices: int)   and the number of vertices.

+WeightedGraph(edges: List<WeightedEdge>,   Constructs a weighted graph with the specified edges in a list
  numberOfVertices: int)   and the number of vertices.

+printWeightedEdges(): void   Displays all edges and weights.

+getWeight(int u, int v): double   Returns the weight on the edge from u to v. Throw an exception
                                                  if the edge does not exist.

+addEdge(u: int, v: int, weight: double): void   Adds a weighted edge to the graph and throws an
                                                  `IllegalArgumentException` if u, v, or w is invalid. If
                                                  (u, v) is already in the graph, the new weight is set.

+getMinimumSpanningTree(): MST   Returns a minimum spanning tree starting from vertex 0.

+getMinimumSpanningTree(index: int): MST   Returns a minimum spanning tree starting from vertex v.

+getShortestPath(index: int): ShortestPathTree   Returns all single-source shortest paths.

**WeightedGraph**   **TestWeightedGraph**   **Run**

Minimum Spanning Trees

A graph may have many spanning trees. Suppose that the edges are weighted. A minimum spanning tree is a spanning tree with the minimum total weights. For example, the trees in Figures (b), (c), (d) are spanning trees for the graph in Figure (a). The trees in Figures (c) and (d) are minimum spanning trees.
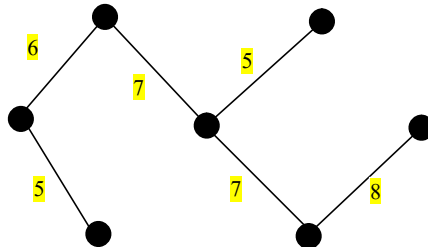
Total w: 42

(b)
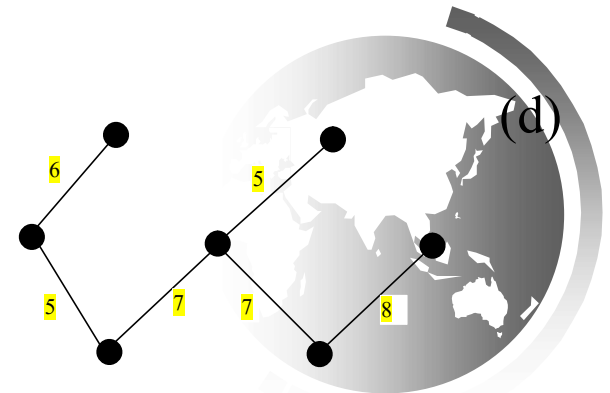
(a)

Total w: 38

Total w: 38

(c)
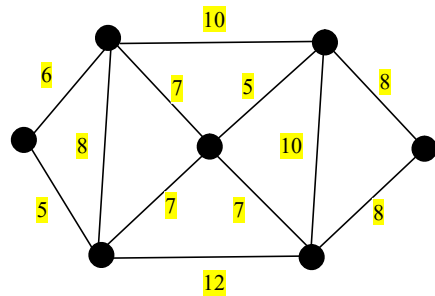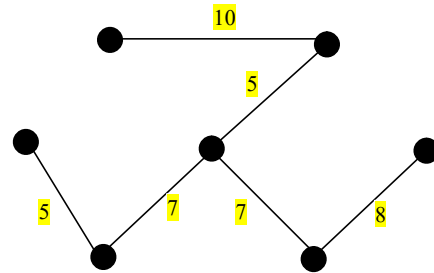
(d)

Prim's Minimum Spanning Tree Algorithm

Input: G = (V, E) with non-negative weights.

Output: a MST

MST minimumSpanningTree() {

  Let V denote the set of vertices in the graph;

  Let T be a set for the vertices in the spanning tree;

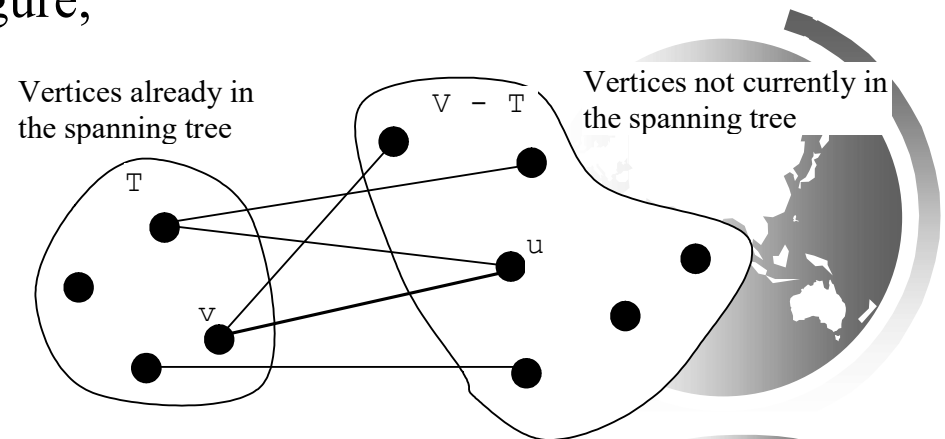 Initially, add the starting vertex to T;

  while (size of T < n) {

    find v in T and u in V – T with the smallest weight

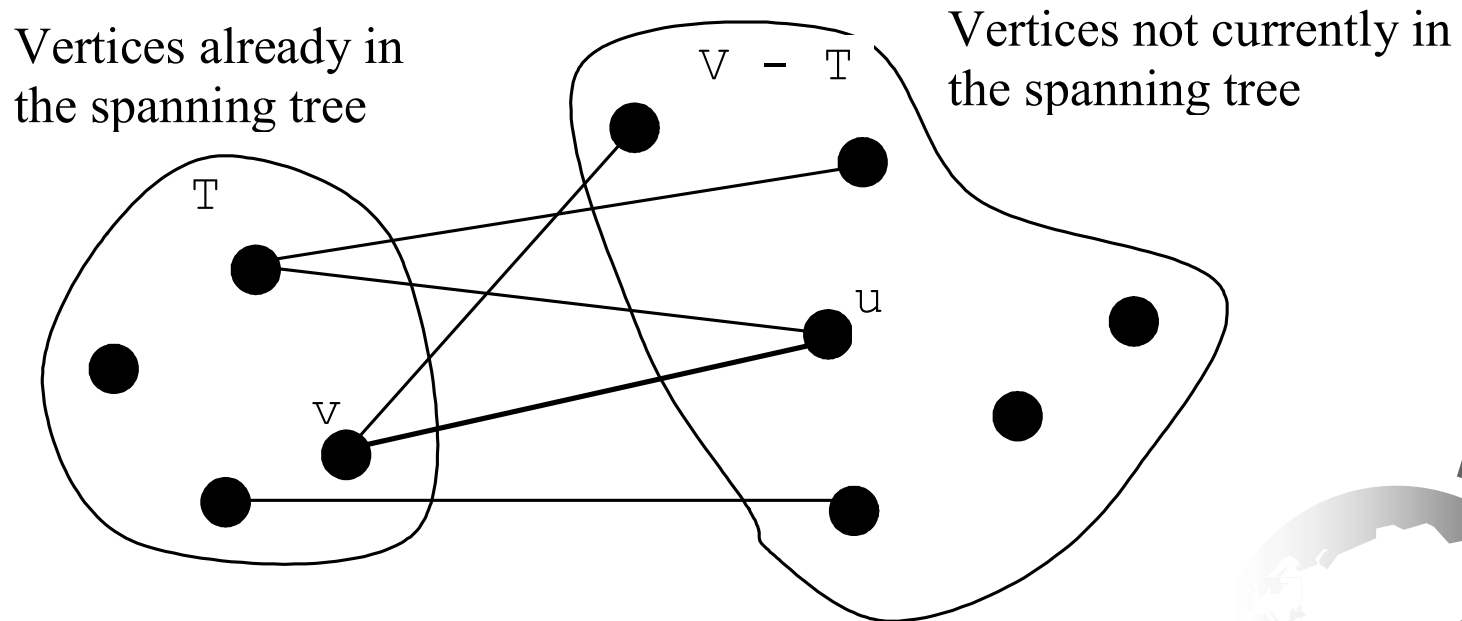   on the edge (u, v), as shown in the figure;

    add u to T;

  }

}

Find a vertex in V-T that has the smallest weighted edge connecting to a vertex in T.

Vertices already in the spanning tree

V – T

Vertices not currently in the spanning tree

T

u

v

Minimum Spanning Tree Algorithm

Vertices already in
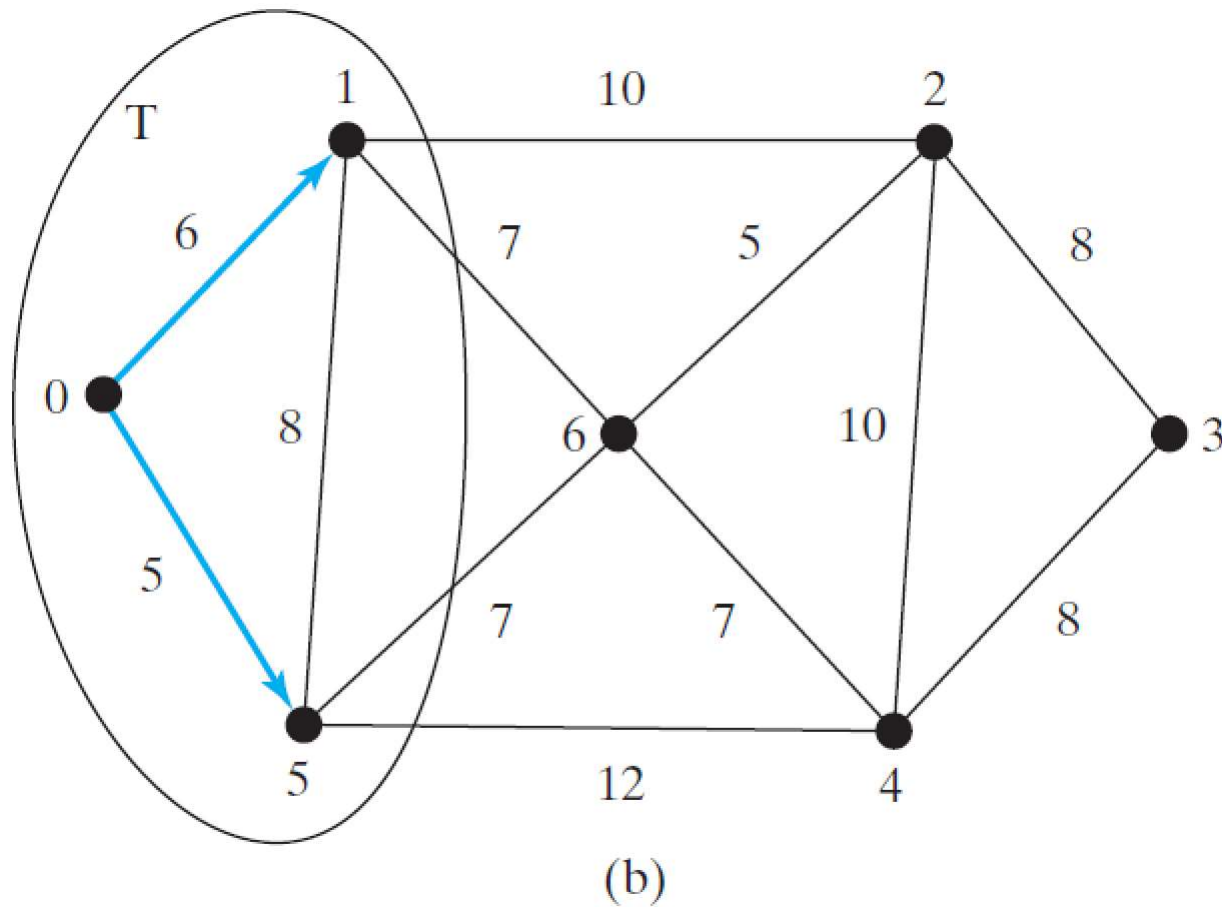the spanning tree

V - T

Vertices not currently in
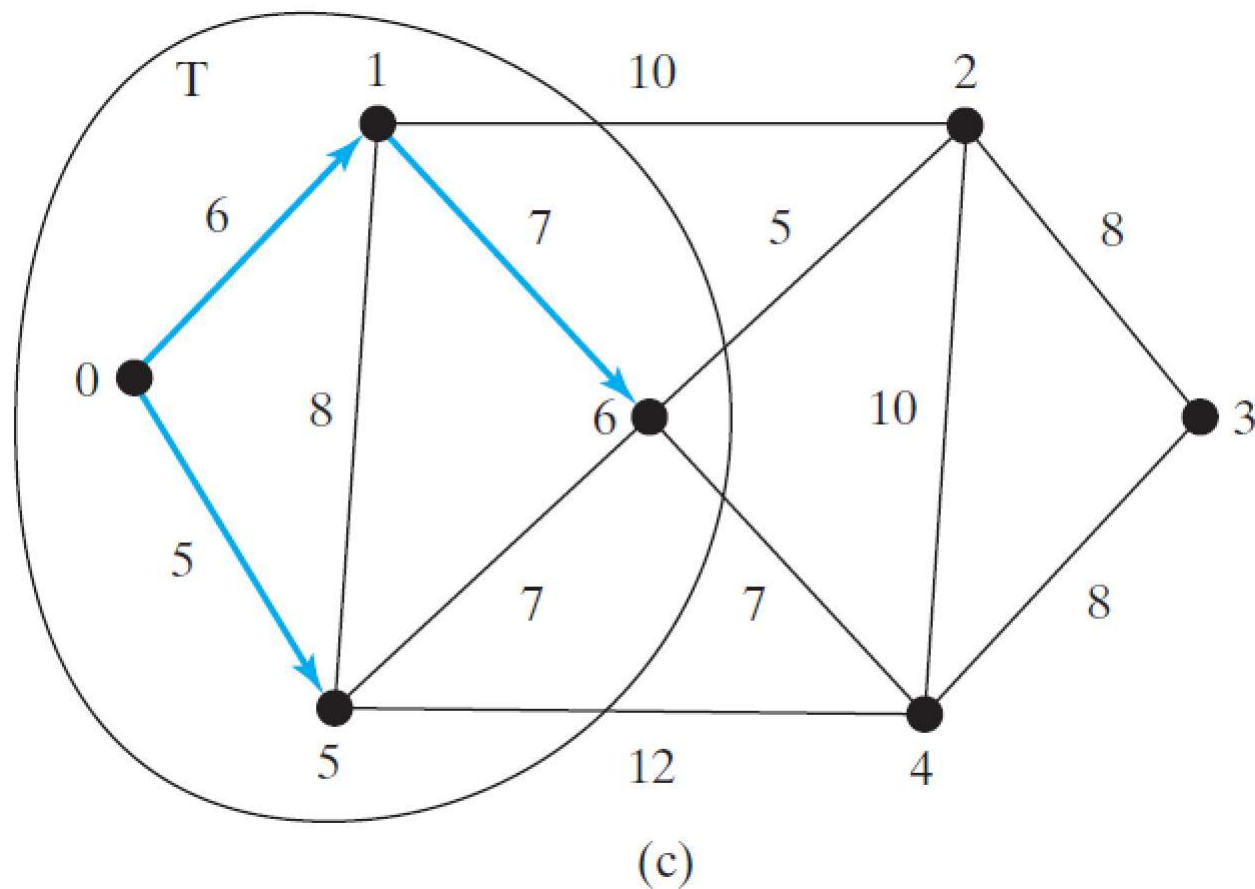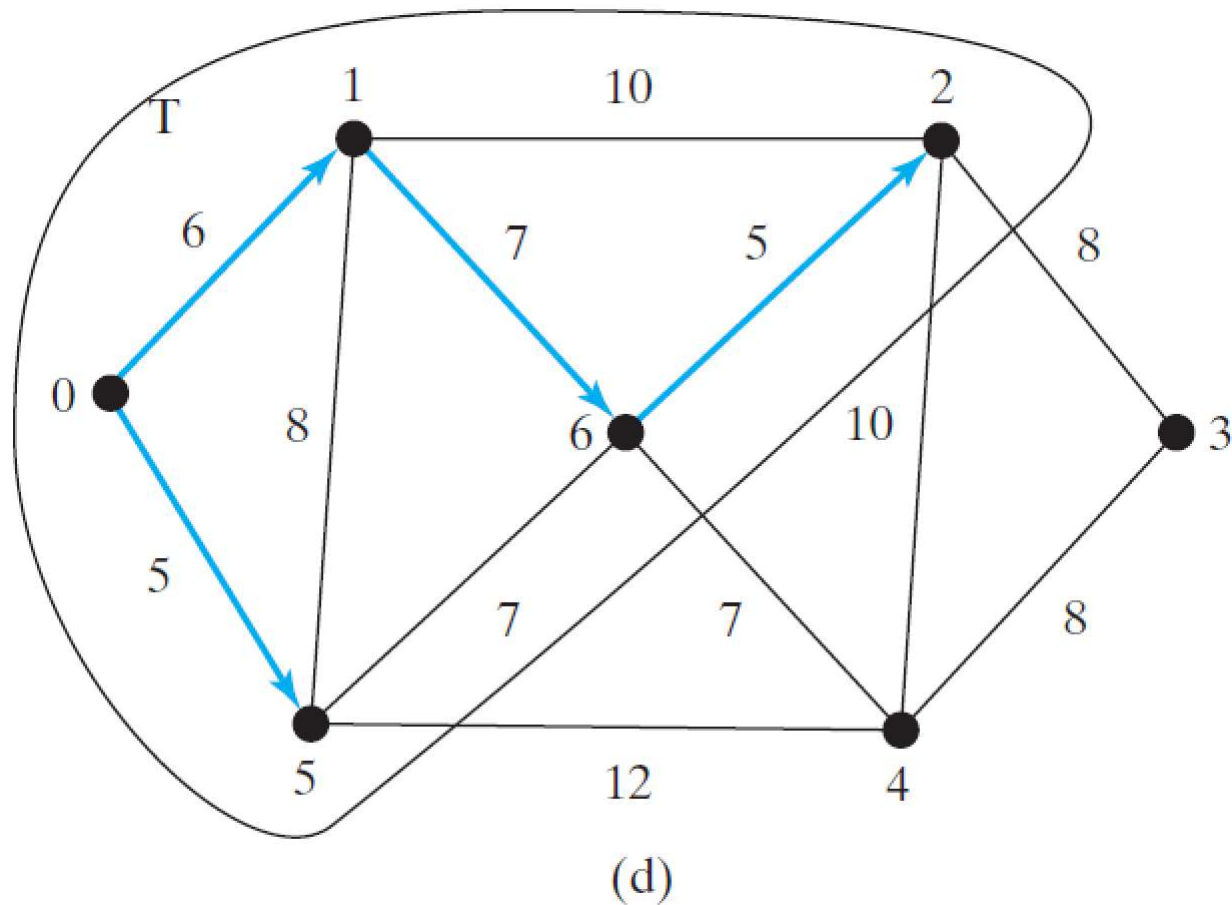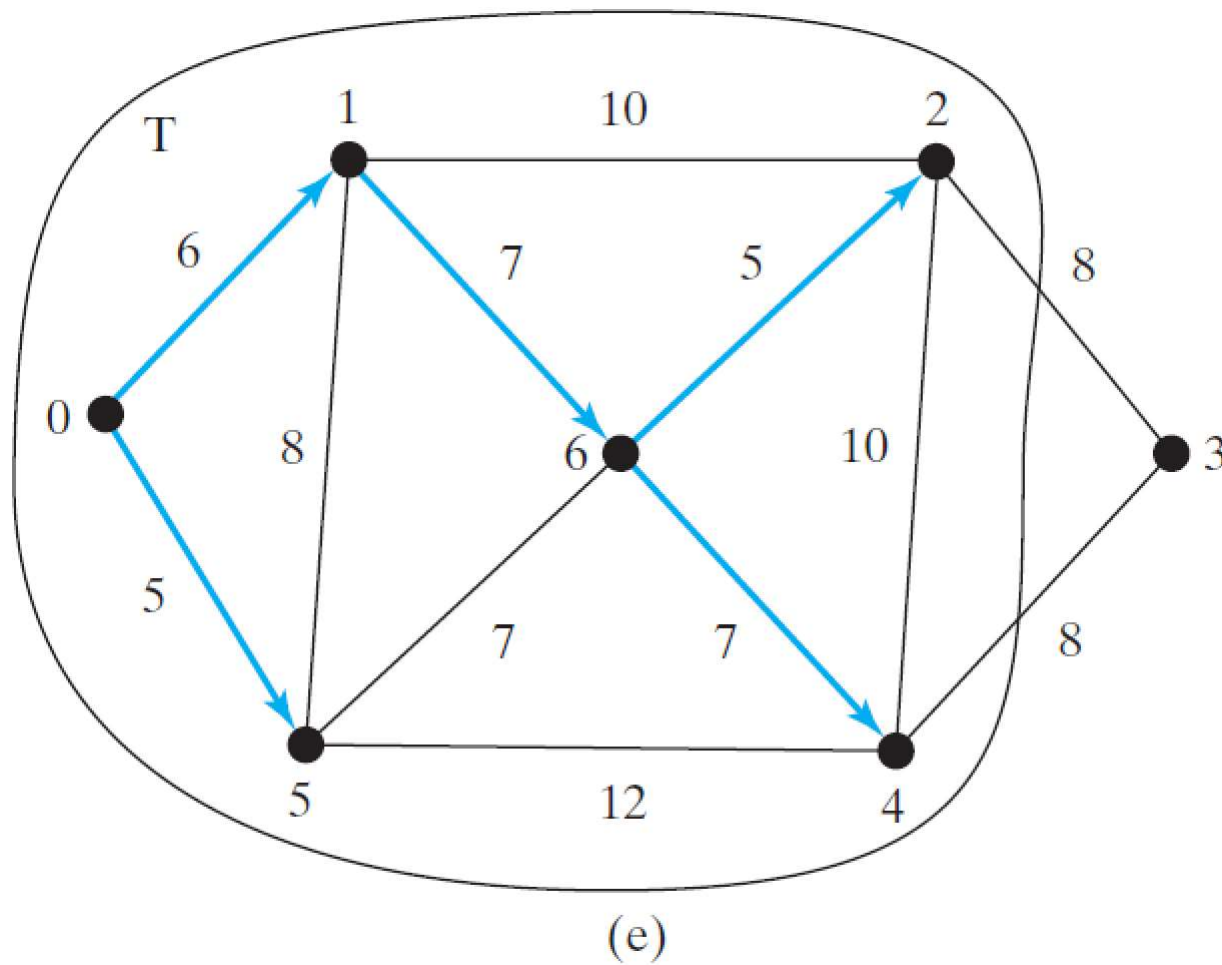the spanning tree

T

u

v

Minimum Spanning Tree Algorithm Example

(a)

Minimum Spanning Tree Algorithm Example

(b)

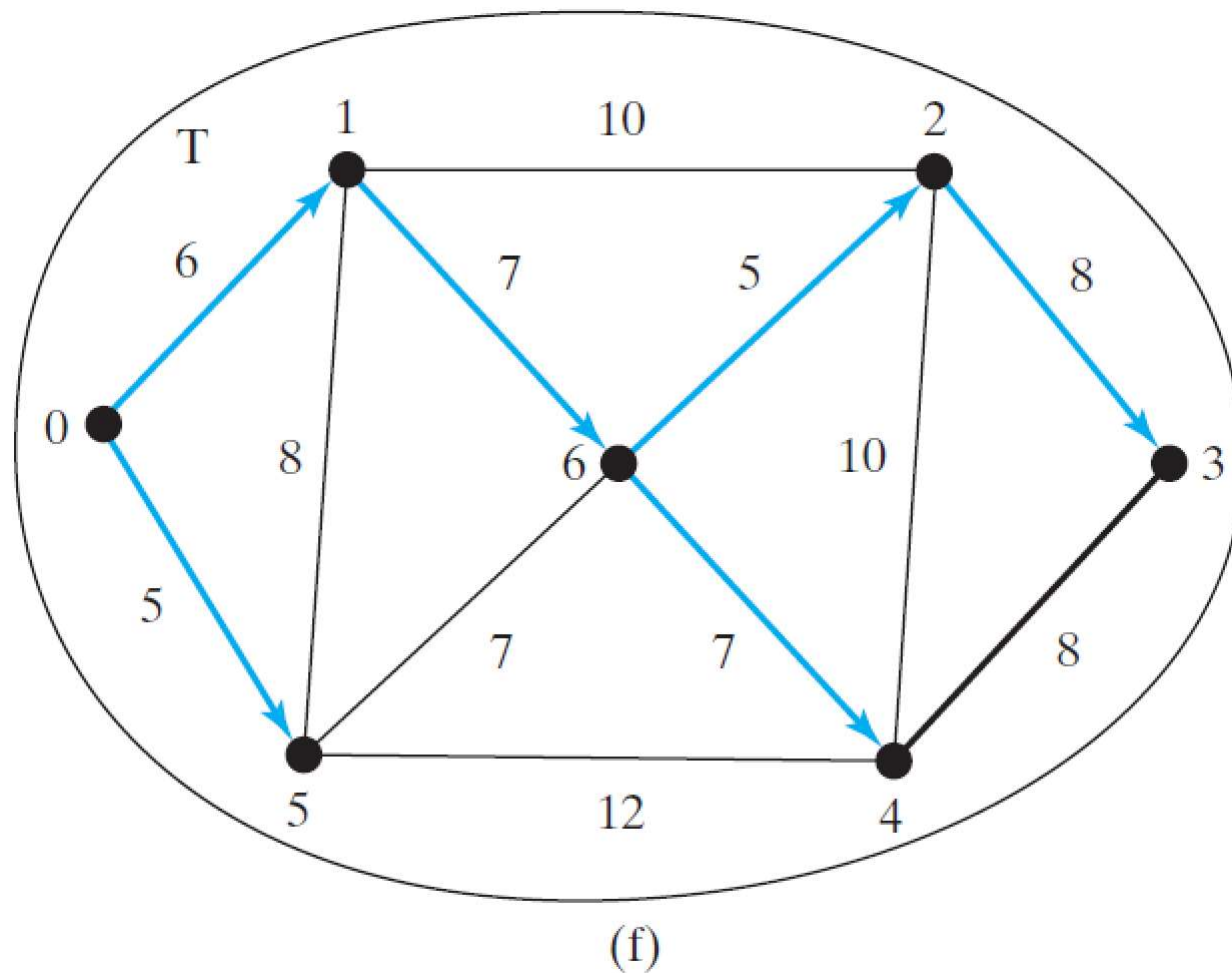# Minimum Spanning Tree Algorithm Example

(c)

Minimum Spanning Tree Algorithm Example

(d)

Minimum Spanning Tree Algorithm Example

(e)

Minimum Spanning Tree Algorithm Example

(f)
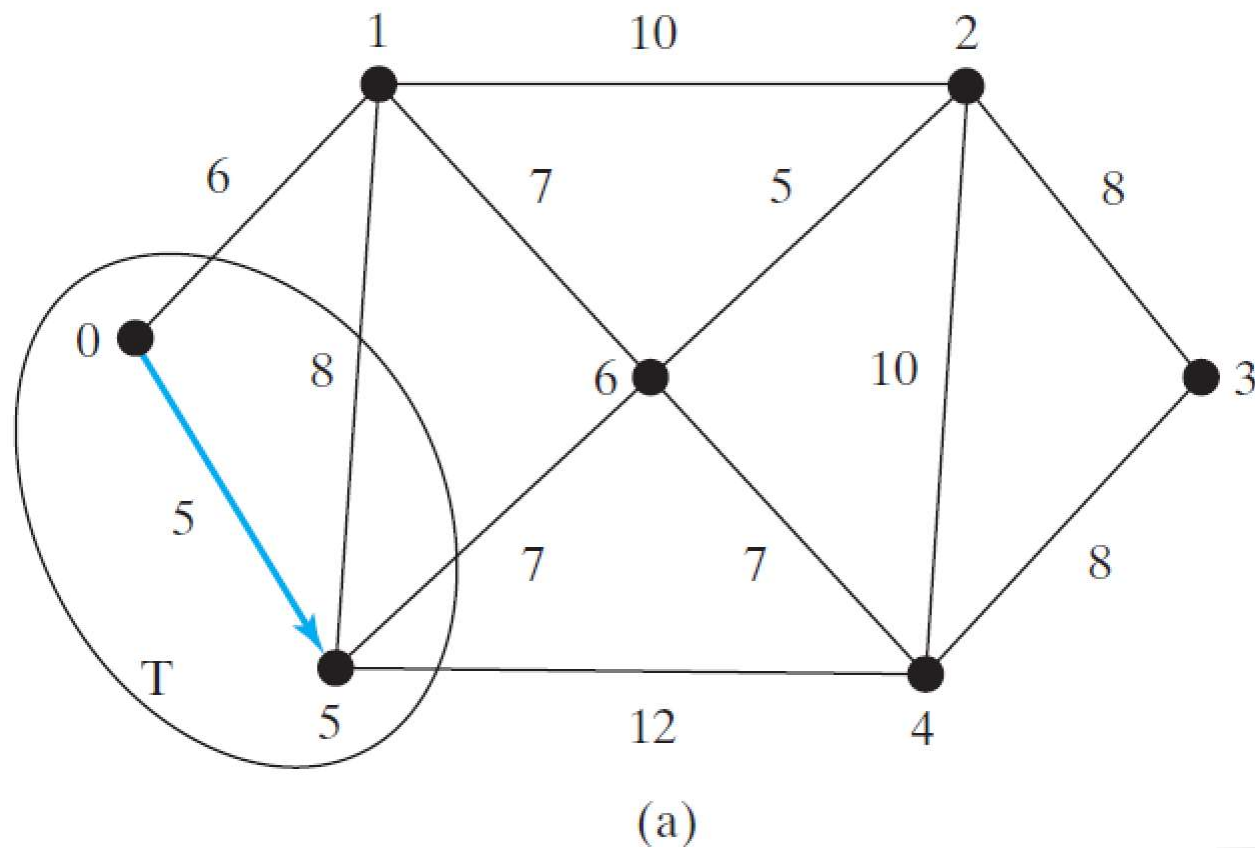
Refined Version of Prim's Minimum Spanning Tree Algorithm

Input: a graph G = (V, E) with non-negative weights
Output: a minimum spanning tree with the starting vertex s as the root

```
1  MST getMinimumSpanngingTree(s) {
2    Let T be a set that contains the vertices in the spanning tree;
3    Initially T is empty;
4    Set cost[s] = 0; and cost[v] = infinity for all other vertices in V;
5
6    while (size of T < n) {
7      Find u not in T with the smallest cost[u];
8      Add u to T;
9      for (each v not in T and (u, v) in E)
10       if (cost[v] > w(u, v)) {
11         cost[v] = w(u, v); parent[v] = u;
12       }
13   }
```

Implementing MST Algorithm

```
UnweightedGraph<V>.SearchTree
```

△

WeightedGraph<V>.MST
-totalWeight: double
+MST(root: int, parent: int[], searchOrder: List<Integer> totalWeight: double)
+getTotalWeight(): double

Total weight of the tree.

Constructs an MST with the specified root, parent array, searchOrder, and total weight for the tree.

Returns the totalWeight of the tree.

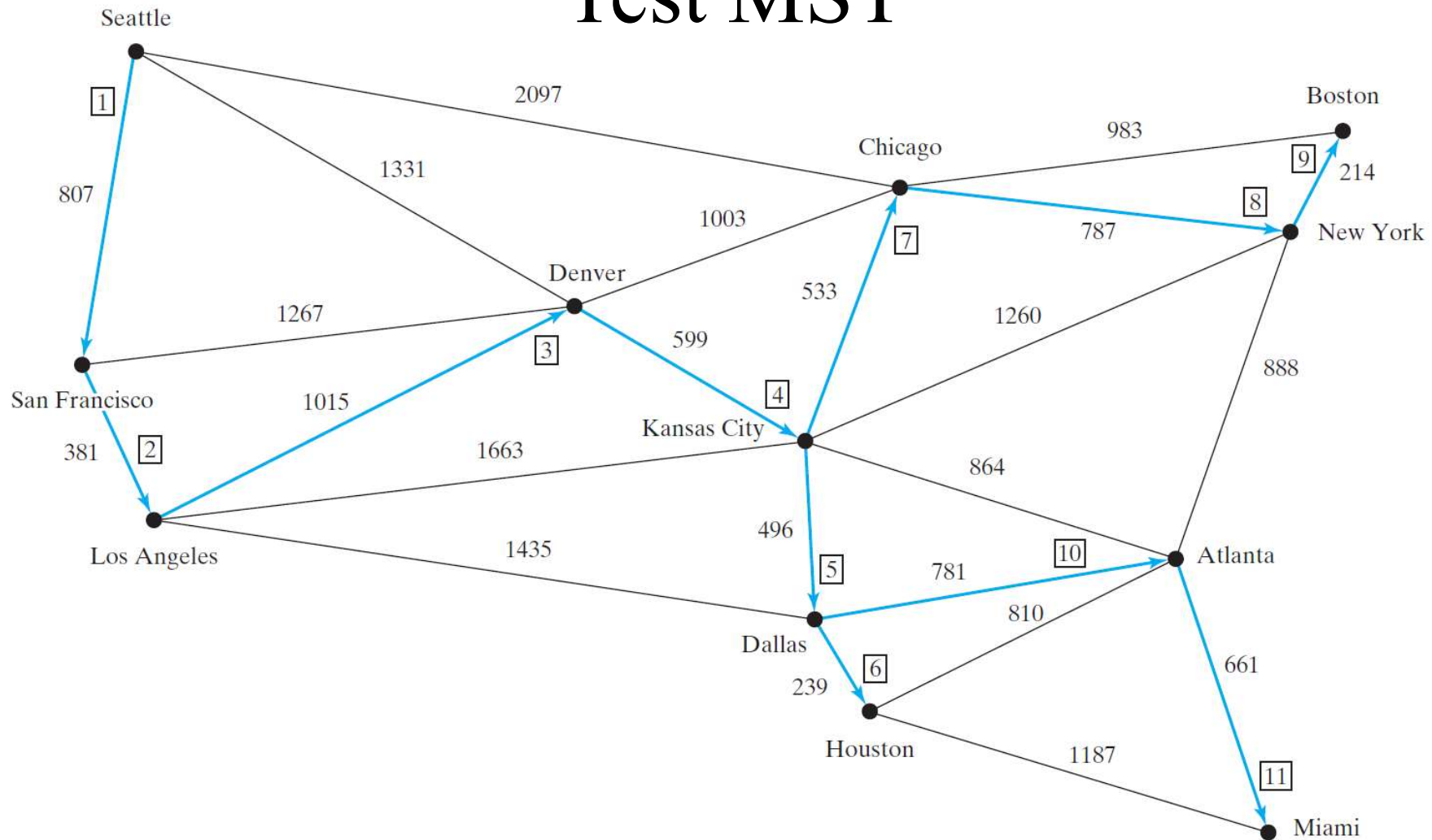# Time Complexity

Note that testing whether a vertex **i** is in **T** by invoking **T.conatins(i)** takes **O(n)** time, since **T** is a list. Therefore, the overall time complexity for this implemention is $O(n^3)$. Interested readers may see Programming Exercise 29.20 for improving the implementation and reduce the complexity to $O(n^2)$.

Test MST

TestMinimumSpanningTree   Run

Shortest Path

§29.1 introduced the problem of finding the shortest distance between two cities for the graph in Figure 29.1. The answer to this problem is to find a shortest path between two vertices in the graph.
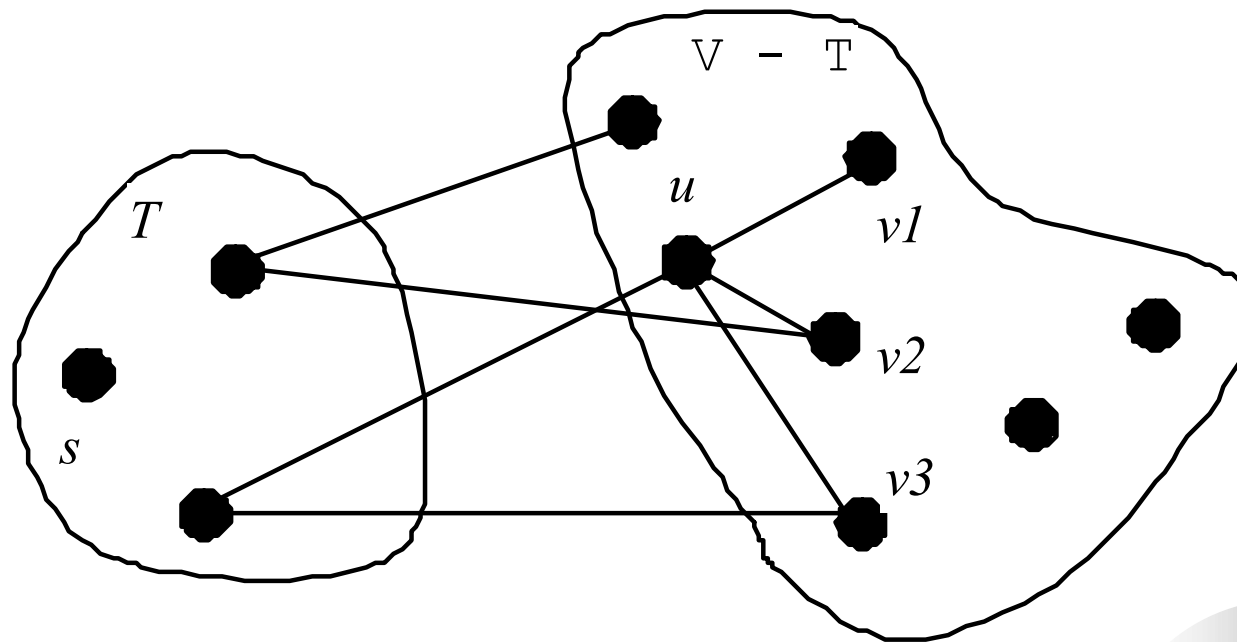
Single Source Shortest Path Algorithm

Input: a graph G = (V, E) with non-negative weights

Output: a shortest path tree with the source vertex s as the root

```
 1  ShortestPathTree getShortestPath(s) {
 2    Let T be a set that contains the vertices whose
 3      paths to s are known; Initially T is empty;
 4    Set cost[s] = 0; and cost[v] = infinity for all other vertices in V;
 5
 6    while (size of T < n) {
 7      Find u not in T with the smallest cost[u];
 8      Add u to T;
 9      for (each v not in T and (u, v) in E)
10        if (cost[v] > cost[u] + w(u, v)) {
11          cost[v] = cost[u] + w(u, v); parent[v] = u;
12        }
13    }
14  }
```

Single Source Shortest Path Algorithm

T contains vertices whose shortest path to s are known

V-T contains vertices whose shortest path to s are not known yet

Before moving u to T

Single Source Shortest Path Algorithm
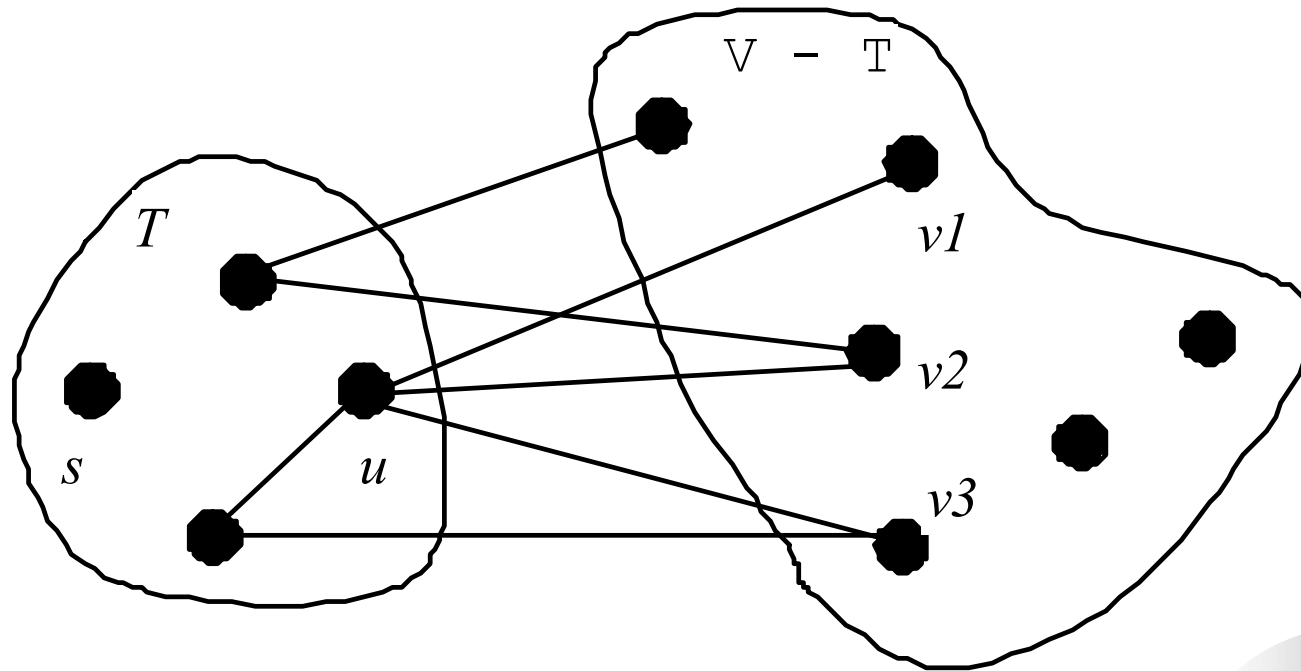

T contains vertices whose shortest path to s are known

V-T contains vertices whose shortest path to s are not known yet

After moving u to T

SP Algorithm Example (Step 0)

(a)
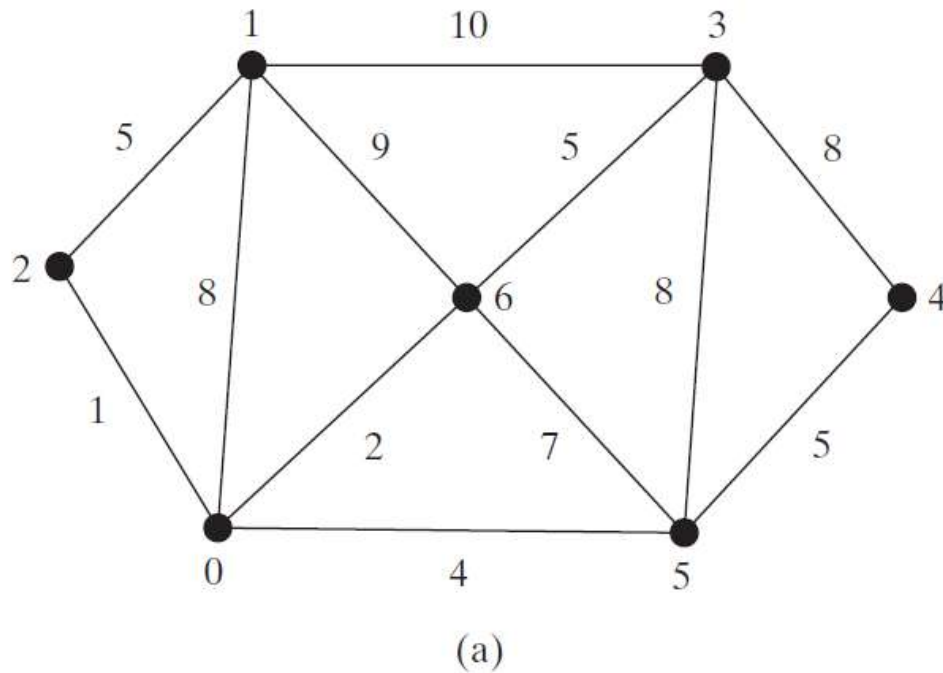
cost

∞	0	∞	∞	∞	∞	∞
0	1	2	3	4	5	6

parent

	−1					
0	1	2	3	4	5	6

(b)

SP Algorithm Example (Step 1)

(a)
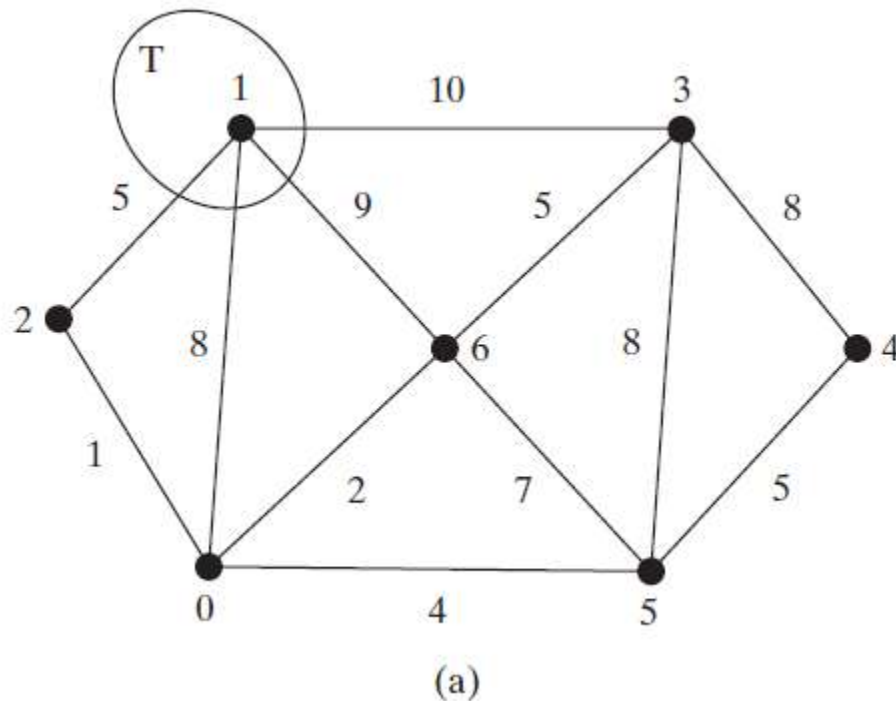
cost

8	0	5	10	∞	∞	9
0	1	2	3	4	5	6

parent

1	−1	1	1			1
0	1	2	3	4	5	6

(b)

SP Algorithm Example (Step 2)

(a)

(b)

SP Algorithm Example (Step 3)

(a)
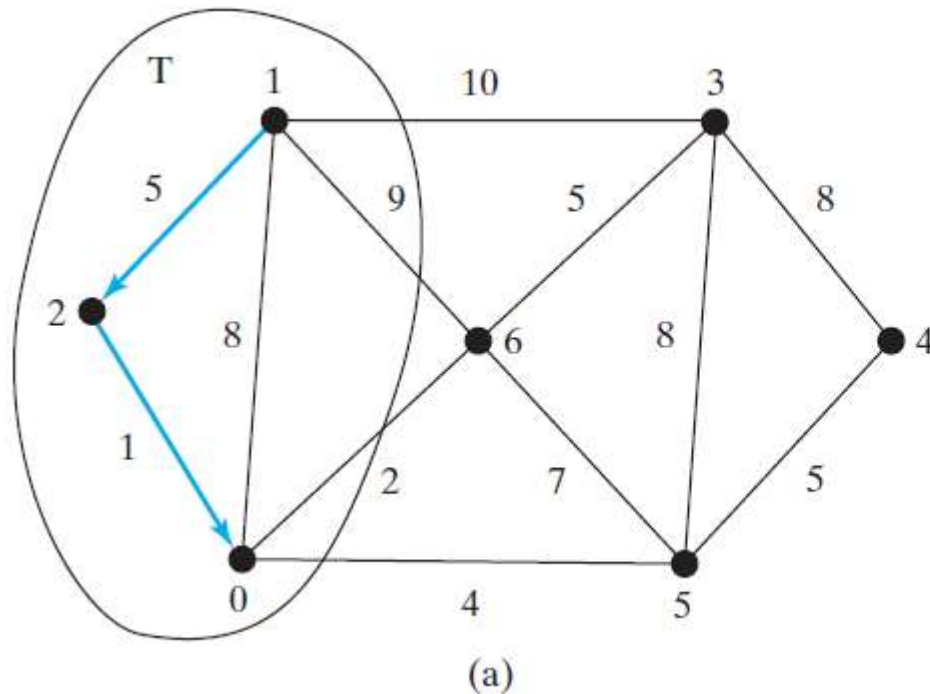
cost

6	0	5	10	∞	10	8
0	1	2	3	4	5	6

parent

2	−1	1	1		0	0
0	1	2	3	4	5	6

(b)

SP Algorithm Example (Step 4)

cost

6	0	5	10	∞	10	8
0	1	2	3	4	5	6

parent

2	−1	1	1		0	0
0	1	2	3	4	5	6

(a)

(b)

SP Algorithm Example (Step 5)
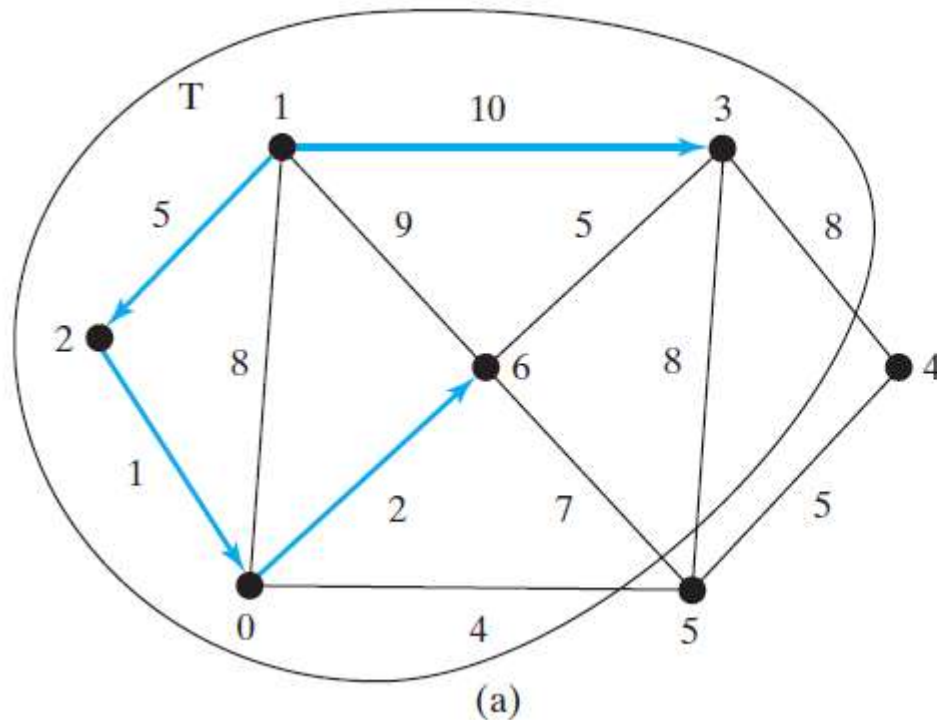
SP Algorithm Example (Step 6)

cost

6	0	5	10	15	10	8
0	1	2	3	4	5	6

parent

2	–1	1	1	5	0	0
0	1	2	3	4	5	6

(a)   (b)

SP Algorithm Example (Step 7)
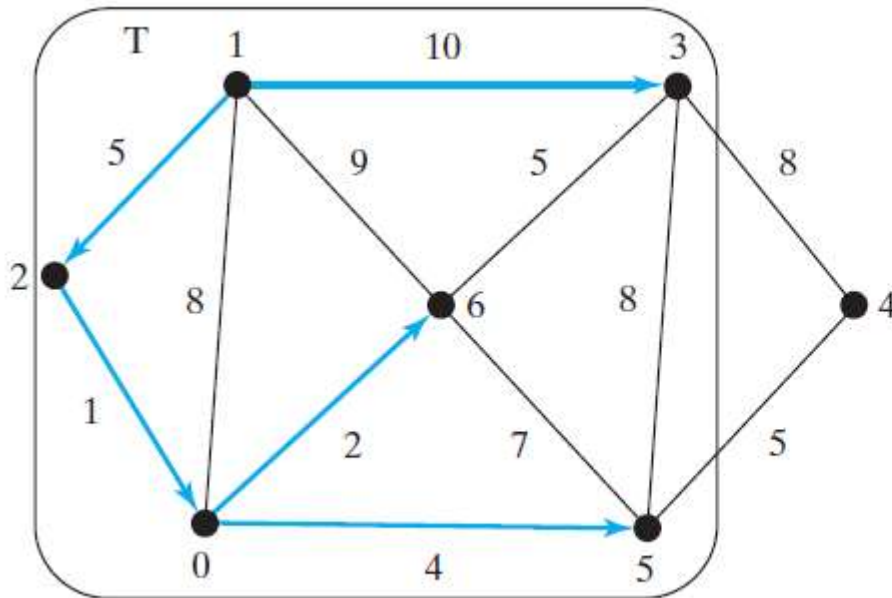
(a)

cost

6	0	5	10	15	10	8
0	1	2	3	4	5	6

parent

2	–1	1	1	5	0	0
0	1	2	3	4	5	6

(b)

SP Algorithm Implementation

```
┌─────────────────────────────────────────────────┐
│        UnweightedGraph<V>.SearchTree             │
└─────────────────────────────────────────────────┘
                        △
                        │
                        │
┌─────────────────────────────────────────────────┐
│        WeightedGraph<V>.ShortestPathTree         │
├─────────────────────────────────────────────────┤
│ -cost: double[]                                  │
├─────────────────────────────────────────────────┤
│ +ShortestPathTree(source: int, parent: int[],    │
│   searchOrder: List<Integer>, cost: double[])    │
│ +getCost(v: int): double                         │
│ +printAllPaths(): void                           │
└─────────────────────────────────────────────────┘
```

cost[v] stores the cost for the path from the source to v.

Constructs a shortest path tree with the specified source, parent array, searchOrder, and cost array.

Returns the cost for the path from the source to vertex v.

Displays all paths from the source.

TestShortestPath   Run

Time Complexity

Same as the Prim's MST, O(n^3) and can be reduced to O(n^2).

SP Algorithm Example

Seattle
11
2097
Boston
983
3
807
1331
Chicago
214
1003
2
787
New York
Denver
1003
533
4
1260
1267
10
599
888
San Francisco
1
1015
Kansas City
381
1663
864
8
7
496
Los Angeles
1435
Atlanta
5
781
810
Dallas
6
661
239
Houston
1187
9
Miami
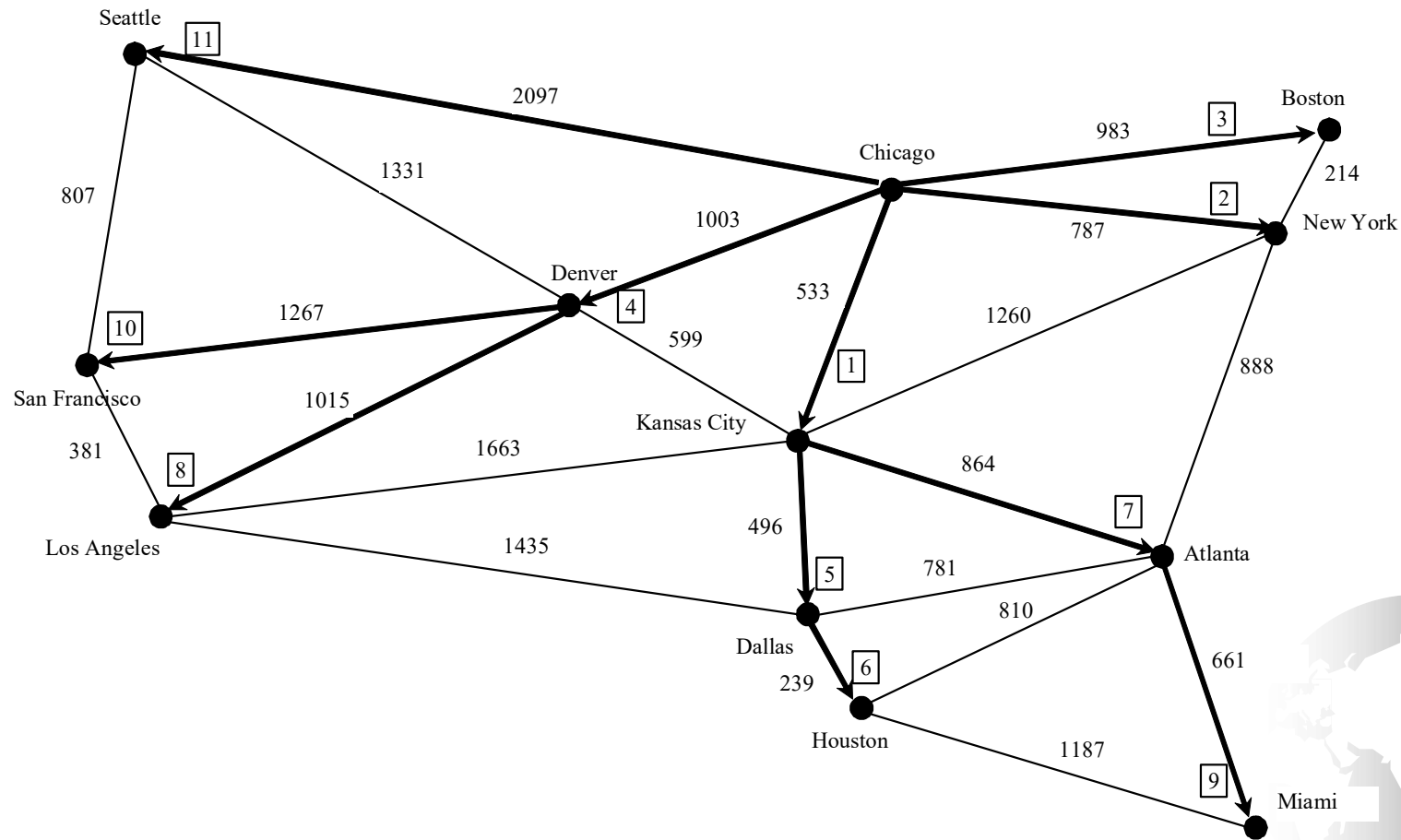
Shortest Path Animation

www.cs.armstrong.edu/liang/animation/Shortest
PathAnimation.html

The Weighted Nine Tail Problem

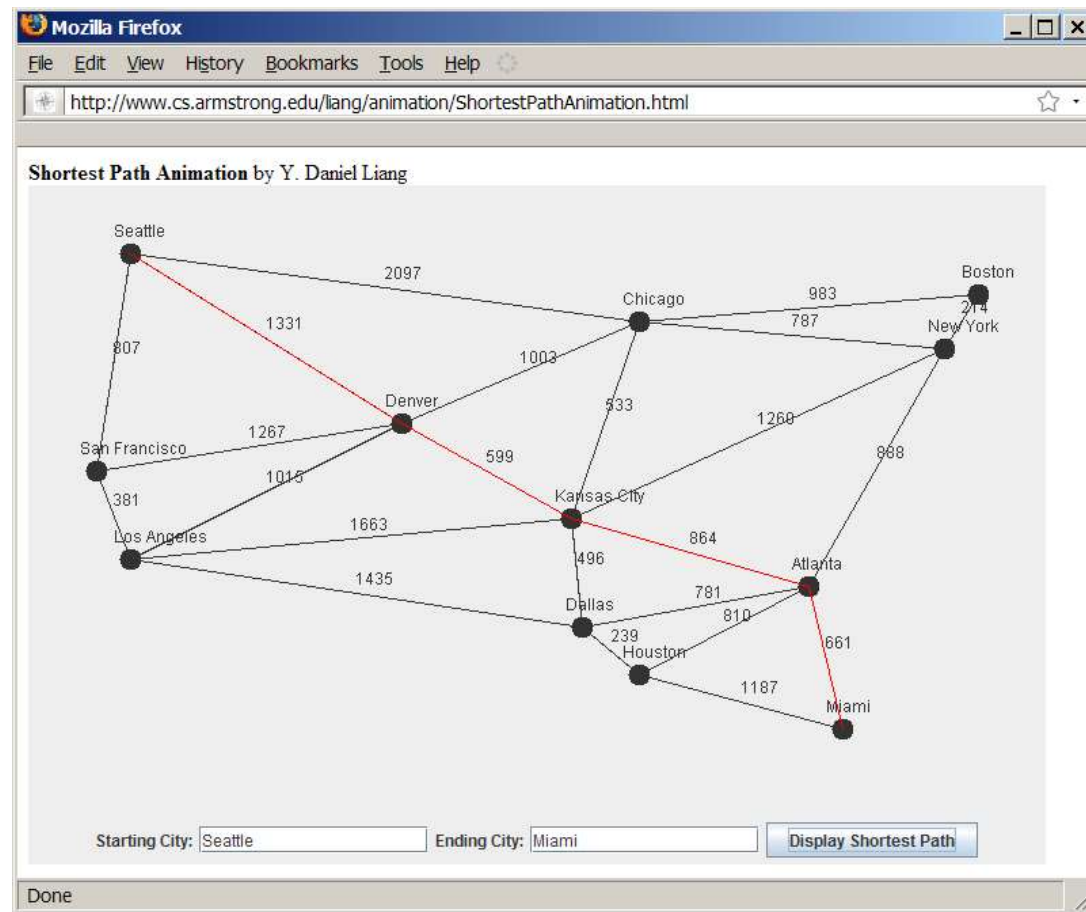The nine tail problem is to find the minimum number of the moves that lead to all coins face down. Each move flips a head coin and its neighbors. The weighted nine tail problem assigns the number of the flips as a weight on each move. For example, you can move from the coins in (a) to (b) by flipping the three coins. So the weight for this move is 3.

(a)

H	H	H
T	T	T
H	H	H

(b)

T	T	H
H	T	T
H	H	H

WeightedNineTailModel

NineTailModel
#tree: UnweightedGraph<Integer>.SeachTree
+NineTailModel() +getShortestPath(nodeIndex: int): List<Integer> -getEdges(): List<AbstractGraph.Edge> +getNode(index: int): char[] +getIndex(node: char[]): int +getFlippedNode(node: char[], position: int): int +flipACell(node: char[], row: int, column: int): void +printNode(node: char[]): void

A tree rooted at node 511.

Constructs a model for the nine tails problem and obtains the tree.

Returns a path from the specified node to the root. The path returned consists of the node labels in a list.

Returns a list of Edge objects for the graph.

Returns a node consisting of nine characters of Hs and Ts.

Returns the index of the specified node.

Flips the node at the specified position and returns the index of the flipped node.

Flips the node at the specified row and column.

Displays the node on the console.

WeightedNineTailModel
+WeightedNineTailModel() +getNumberOfFlips(u: int): int -getNumberOfFlips(u: int, v: int): int -getEdges(): List<WeightedEdge>

Constructs a model for the weighted nine tails problem and obtains a ShortestPathTree rooted from the target node.

Returns the number of flips from node u to the target node 511.

Returns the number of different cells between the two nodes.

Gets the weighted edges for the weighted nine tails problem.

NineTailModel   WeightedNineTailModel   WeightedNineTail   Run