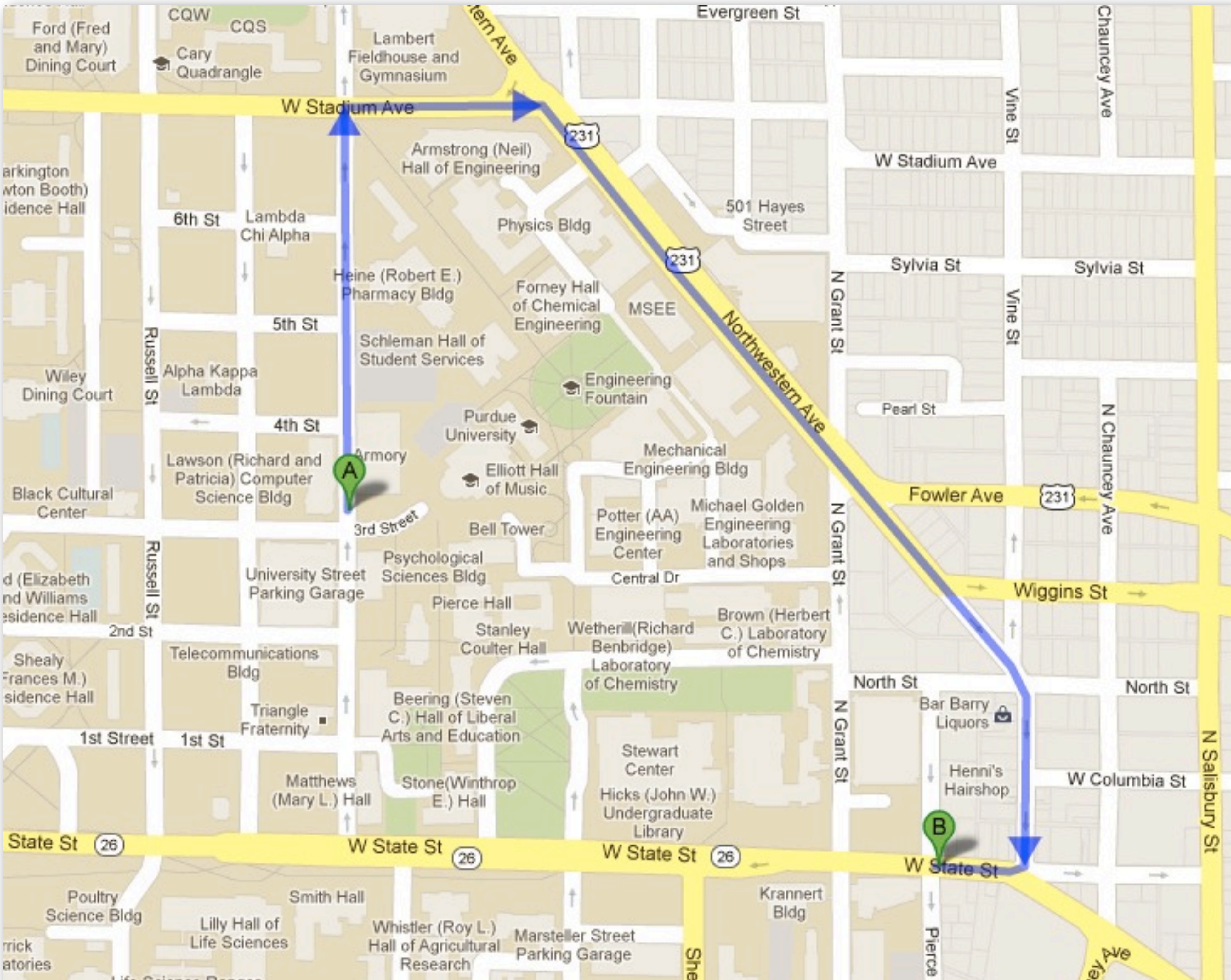
Shortest Paths

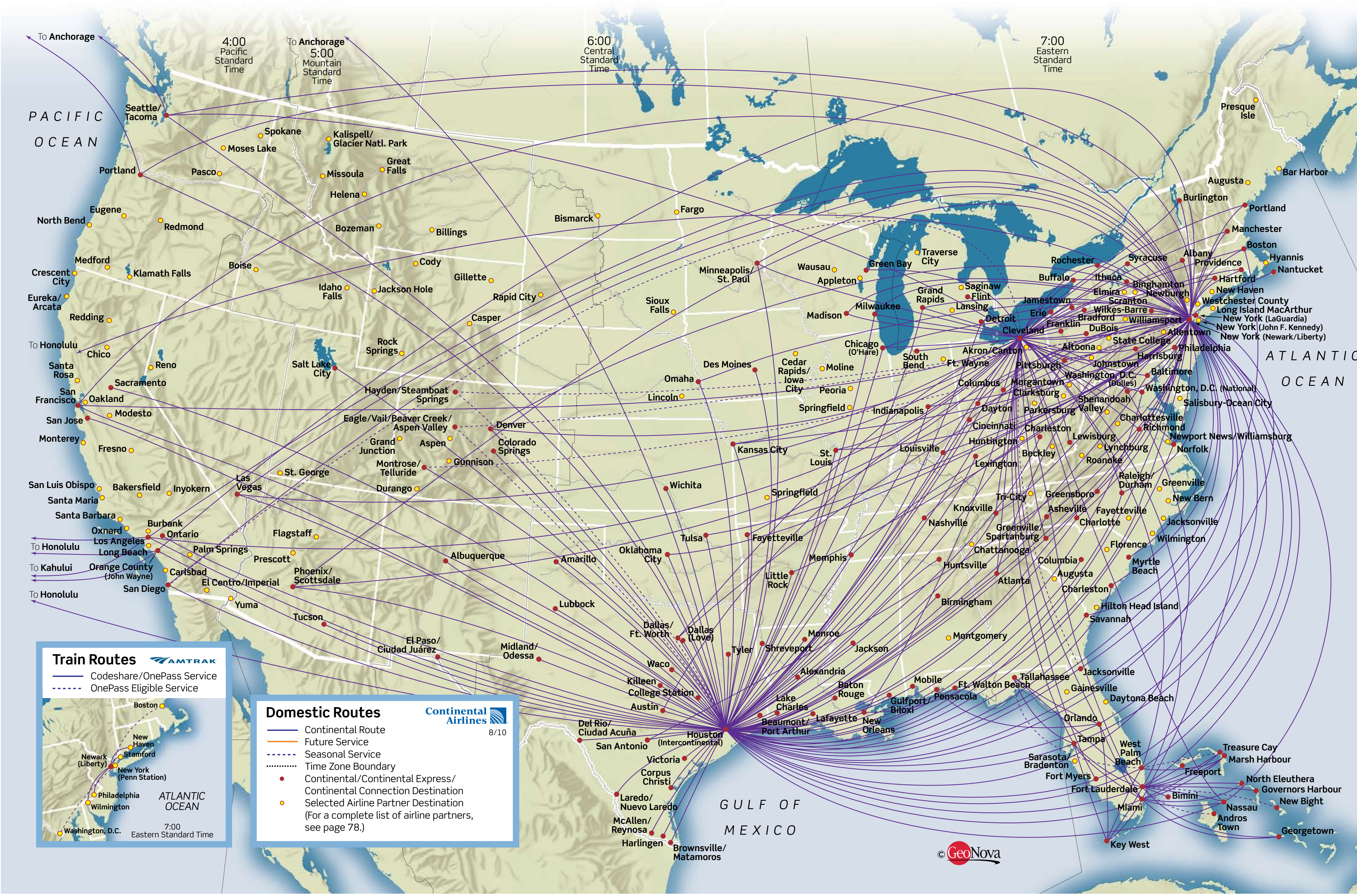
- edge-weighted digraph API
- shortest-paths properties
- Dijkstra's algorithm
- edge-weighted DAGs
- negative weights

Google maps



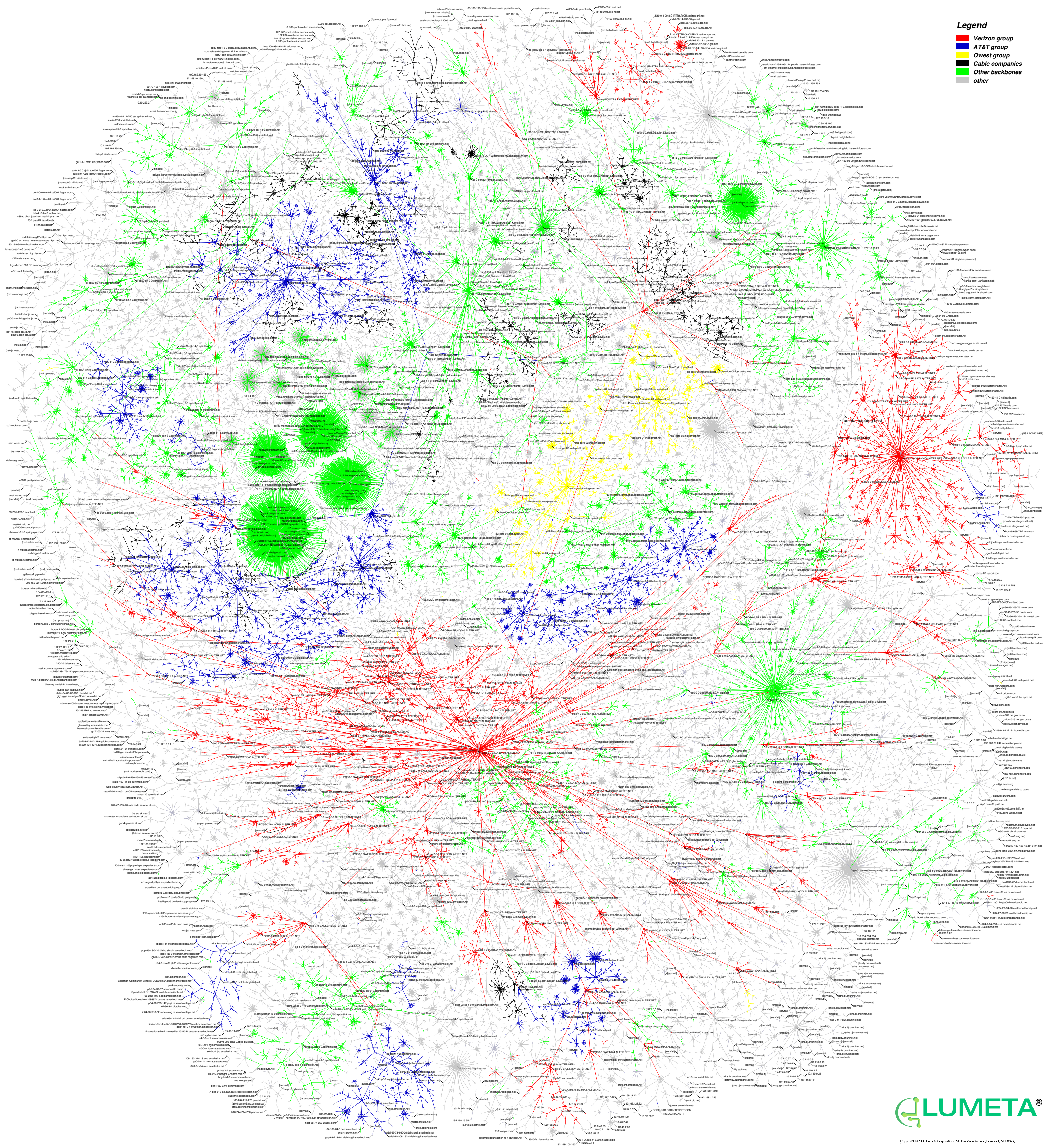
W Stadium Ave
Northwestern Ave
Fowler Ave
Wiggins St
W State St
State St
N Grant St
Russell St
Vine St
Sylvia St
North St
W Columbia St
N Salisbury St
N Chauncey Ave
Evergreen St
Pearl St
6th St
5th St
4th St
3rd Street
2nd St
1st Street
1st St
Central Dr
Armstrong (Neil) Hall of Engineering
Physics Bldg
Forney Hall of Chemical Engineering
MSEE
Engineering Fountain
Purdue University
Elliott Hall of Music
Bell Tower
Mechanical Engineering Bldg
Michael Golden Engineering Laboratories and Shops
Potter (AA) Engineering Center
Lawson (Richard and Patricia) Computer Science Bldg
Armory
Lambert Fieldhouse and Gymnasium
Cary Quadrangle
Ford (Fred and Mary) Dining Court
Wiley Dining Court
Black Cultural Center
Heine (Robert E.) Pharmacy Bldg
Schleman Hall of Student Services
Psychological Sciences Bldg
University Street Parking Garage
Pierce Hall
Stanley Coulter Hall
Telecommunications Bldg
Triangle Fraternity
Beering (Steven C.) Hall of Liberal Arts and Education
Stewart Center
Hicks (John W.) Undergraduate Library
Brown (Herbert C.) Laboratory of Chemistry
Wetherill (Richard Benbridge) Laboratory of Chemistry
Matthews (Mary L.) Hall
Stone (Winthrop E.) Hall
Smith Hall
Lilly Hall of Life Sciences
Whistler (Roy L.) Hall of Agricultural Research
Marsteller Street Parking Garage
Krannert Bldg
Poultry Science Bldg
Bar Barry Liquors
Henni's Hairshop
501 Hayes Street
Lambda Chi Alpha
Alpha Kappa Lambda
A
B
231
26

Continental U.S. routes (August 2010)



http://www.continental.com/web/en-US/content/travel/routes

Shortest outgoing routes on the Internet from Lumeta headquarters



- Verizon group
- AT&T group
- Qwest group
- Cable companies
- Other backbones
- other

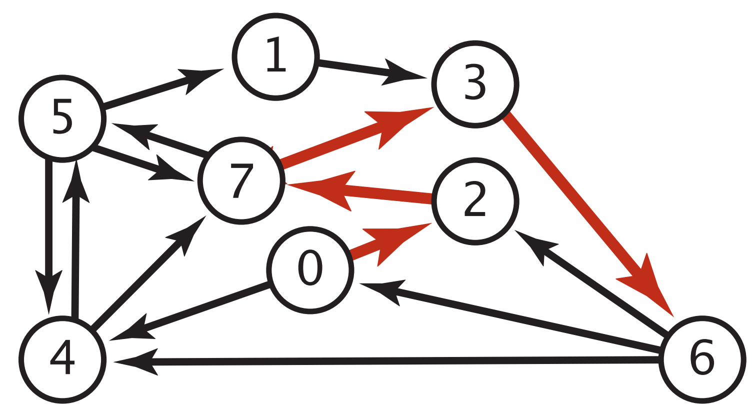
map by Lumeta Corporation, March 8, 2006

Shortest paths in a weighted digraph

Given an edge-weighted digraph, find the shortest (directed) path from s to t.

edge-weighted digraph

4->5	0.35
5->4	0.35
4->7	0.37
5->7	0.28
7->5	0.28
5->1	0.32
0->4	0.38
0->2	0.26
7->3	0.39
1->3	0.29
2->7	0.34
6->2	0.40
3->6	0.52
6->0	0.58
6->4	0.93



shortest path from 0 to 6

0->2	0.26
2->7	0.34
7->3	0.39
3->6	0.52

Shortest path variants

Which vertices?

- Source-sink: from one vertex to another.
- Single source: from one vertex to every other.
- All pairs: between all pairs of vertices.

Restrictions on edge weights?

- Nonnegative weights.
- Arbitrary weights.
- Euclidean weights.

Cycles?

- No cycles.
- No "negative cycles."

Simplifying assumption. There exists a shortest path from s to each vertex v.

Shortest path applications

- Map routing.
- Robot navigation.
- Texture mapping.
- Typesetting in TeX.
- Urban traffic planning.
- Optimal pipelining of VLSI chip.
- Telemarketer operator scheduling.
- Subroutine in advanced algorithms.
- Routing of telecommunications messages.
- Approximating piecewise linear functions.
- Network routing protocols (OSPF, BGP, RIP).
- Exploiting arbitrage opportunities in currency exchange.
- Optimal truck routing through given traffic congestion pattern.

Reference: Network Flows: Theory, Algorithms, and Applications, R. K. Ahuja, T. L. Magnanti, and J. B. Orlin, Prentice Hall, 1993.

Shortest Paths

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- shortest-paths properties
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Weighted directed edge API

`public class DirectedEdge`		
	`DirectedEdge(int v, int w, double weight)`	*weighted edge v→w*
`int`	`from()`	*vertex v*
`int`	`to()`	*vertex w*
`double`	`weight()`	*weight of this edge*
`String`	`toString()`	*string representation*

Idiom for processing an edge **e**: **`int v = e.from(), w = e.to();`**

Weighted directed edge: implementation in Java

Similar to **`Edge`** for undirected graphs, but a bit simpler.

```
public class DirectedEdge
{
   private final int v, w;
   private final double weight;

   public DirectedEdge(int v, int w, double weight)
   {
      this.v = v;
      this.w = w;
      this.weight = weight;
   }

   public int from()
   {  return v;  }

   public int to()
   {  return w;  }

   public int weight()
   {  return weight; }
}
```

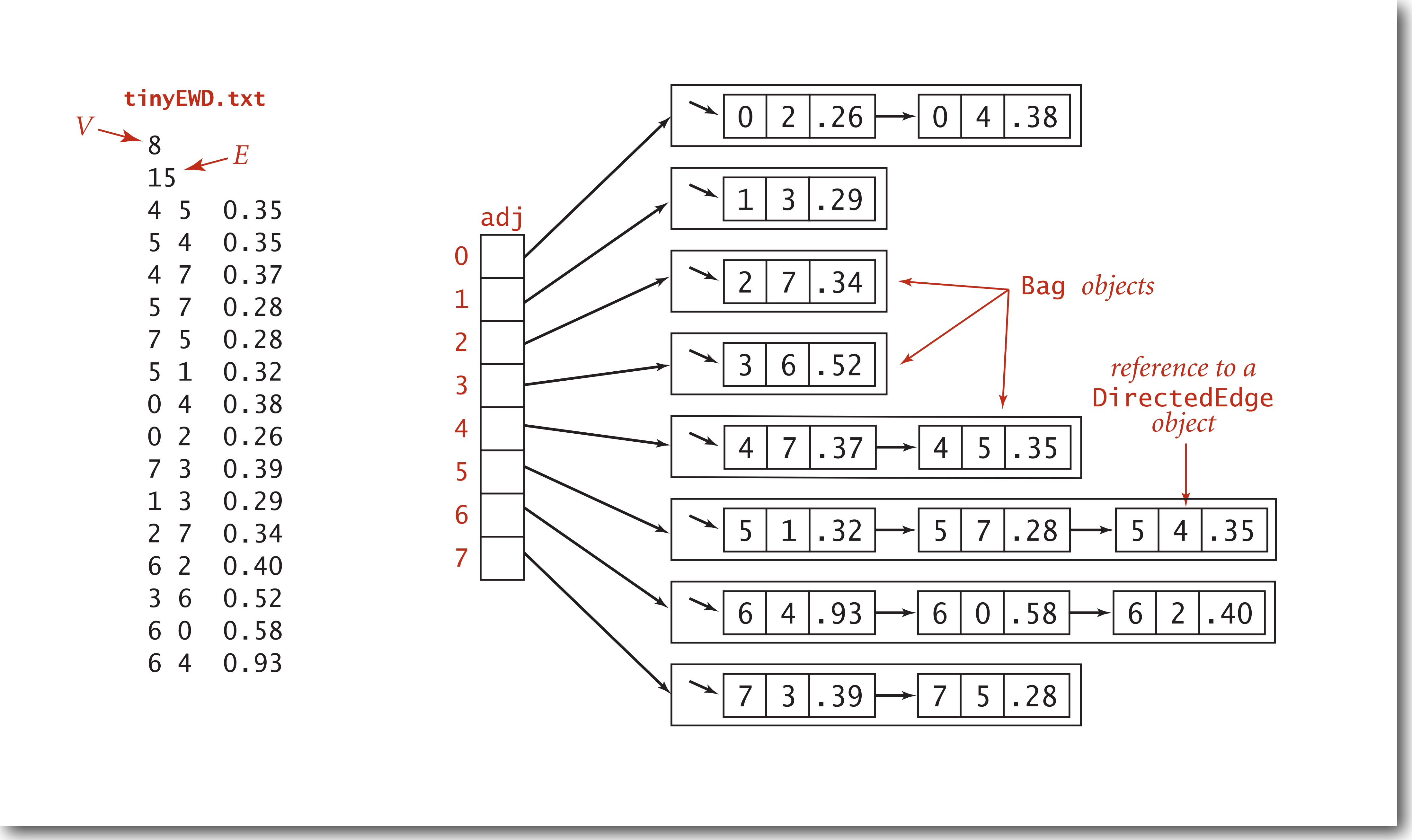
`from()` and **`to()`** replace **`either()`** and **`other()`**

Edge-weighted digraph API

	public class EdgeWeightedDigraph	
	EdgeWeightedDigraph(int V)	*edge-weighted digraph with V vertices*
	EdgeWeightedDigraph(In in)	*edge-weighted digraph from input stream*
void	addEdge(DirectedEdge e)	*add weighted directed edge e*
Iterable<DirectedEdge>	adj(int v)	*edges adjacent from v*
int	V()	*number of vertices*
int	E()	*number of edges*
Iterable<DirectedEdge>	edges()	*all edges in this digraph*
String	toString()	*string representation*

Conventions. Allow self-loops and parallel edges.

Edge-weighted digraph: adjacency-lists representation



Edge-weighted digraph: adjacency-lists implementation in Java

Same as **`EdgeWeightedGraph`** except replace **`Graph`** with **`Digraph`**.

```
public class EdgeWeightedDigraph
{
   private final int V;
   private final Bag<Edge>[] adj;

   public EdgeWeightedDigraph(int V)
   {
      this.V = V;
      adj = (Bag<DirectedEdge>[]) new Bag[V];
      for (int v = 0; v < V; v++)
         adj[v] = new Bag<DirectedEdge>();
   }

   public void addEdge(DirectedEdge e)
   {
      int v = e.from();
      adj[v].add(e);
   }

   public Iterable<DirectedEdge> adj(int v)
   {  return adj[v];  }
}
```

similar to edge-weighted undirected graph, but only add edge to v's adjacency list

Single-source shortest paths API

Goal. Find the shortest path from s to every other vertex.

`public class SP`		
	`SP(EdgeWeightedDigraph G, int s)`	*shortest paths from s in graph G*
`double`	`distTo(int v)`	*length of shortest path from s to v*
`Iterable <DirectedEdge>`	`pathTo(int v)`	*shortest path from s to v*
`boolean`	`hasPathTo(int v)`	*is there a path from s to v?*

```
SP sp = new SP(G, s);
for (int v = 0; v < G.V(); v++)
{
   StdOut.printf("%d to %d (%.2f): ", s, v, sp.distTo(v));
   for (DirectedEdge e : sp.pathTo(v))
      StdOut.print(e + "  ");
   StdOut.println();
}
```

Single-source shortest paths API

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`double`	`distTo(int v)`	*length of shortest path from s to v*
`Iterable <DirectedEdge>`	`pathTo(int v)`	*shortest path from s to v*
`boolean`	`hasPathTo(int v)`	*is there a path from s to v?*

```
% java SP tinyEWD.txt 0
0 to 0 (0.00):
0 to 1 (1.05): 0->4 0.38  4->5 0.35  5->1 0.32
0 to 2 (0.26): 0->2 0.26
0 to 3 (0.99): 0->2 0.26  2->7 0.34  7->3 0.39
0 to 4 (0.38): 0->4 0.38
0 to 5 (0.73): 0->4 0.38  4->5 0.35
0 to 6 (1.51): 0->2 0.26  2->7 0.34  7->3 0.39  3->6 0.52
0 to 7 (0.60): 0->2 0.26  2->7 0.34
```

Shortest Paths

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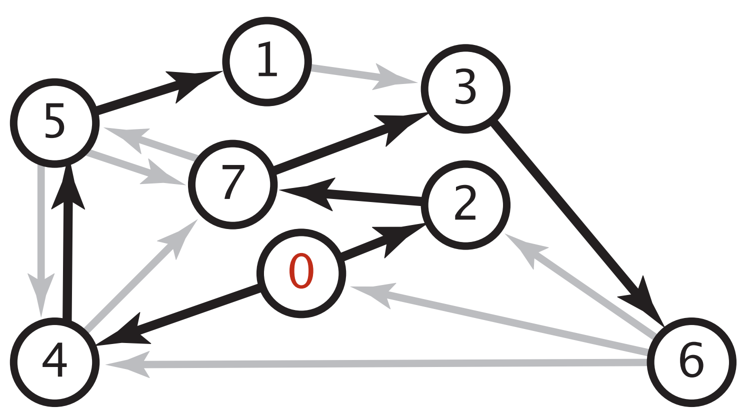
Data structures for single-source shortest paths

Goal. Find the shortest path from s to every other vertex.

Observation. A shortest path tree (SPT) solution exists. Why?

Consequence. Can represent the SPT with two vertex-indexed arrays:

- `distTo[v]` is length of shortest path from s to v.
- `edgeTo[v]` is last edge on shortest path from s to v.



	edgeTo[]	distTo[]
0	null	0
1	5->1 0.32	1.05
2	0->2 0.26	0.26
3	7->3 0.37	0.97
4	0->4 0.38	0.38
5	4->5 0.35	0.73
6	3->6 0.52	1.49
7	2->7 0.34	0.60

shortest path tree from 0

Data structures for single-source shortest paths

Goal. Find the shortest path from s to every other vertex.

Observation. A shortest path tree (SPT) solution exists. Why?

Consequence. Can represent the SPT with two vertex-indexed arrays:

- **`distTo[v]`** is length of shortest path from s to v.
- **`edgeTo[v]`** is last edge on shortest path from s to v.

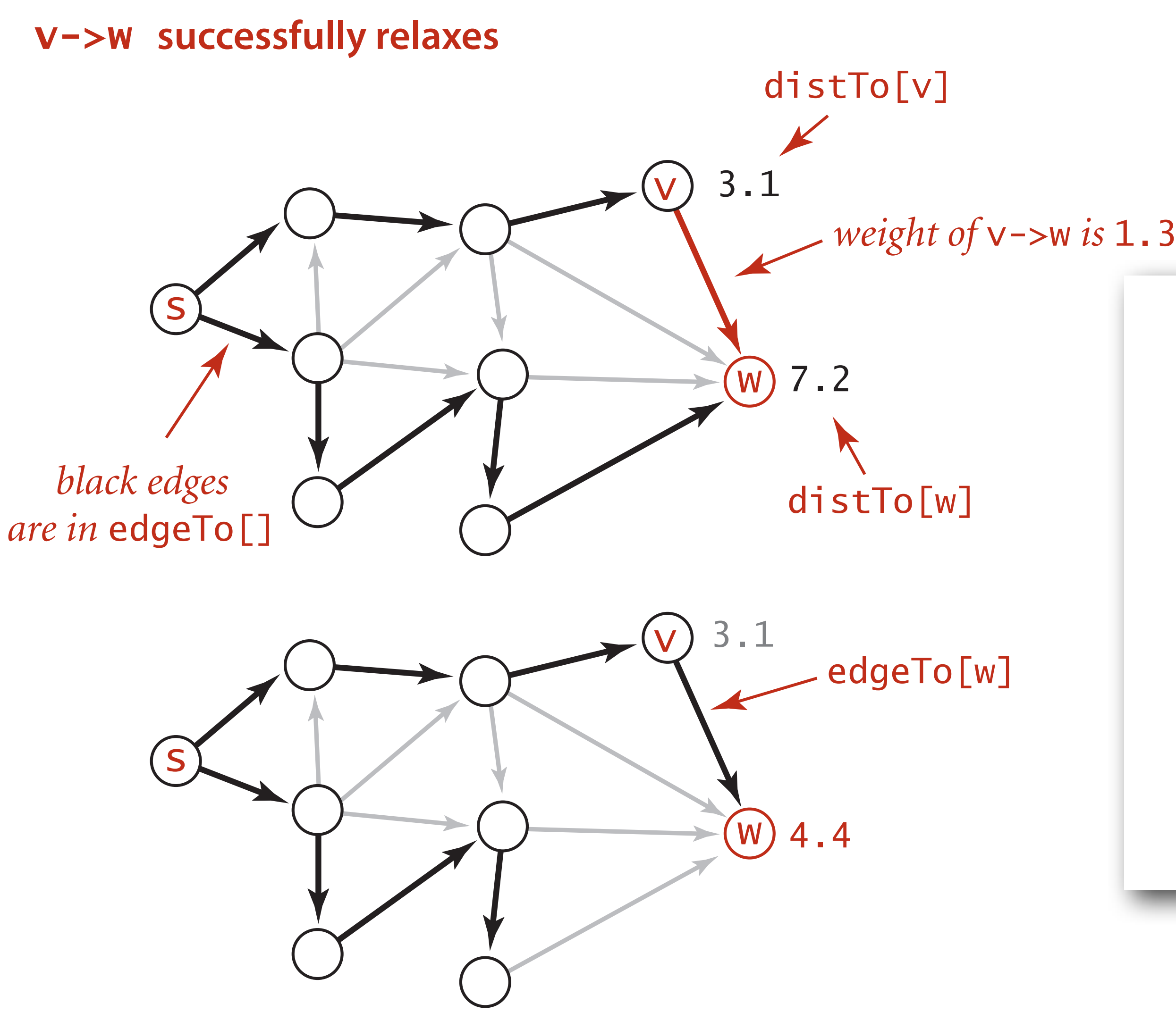
```
public double distTo(int v)
{  return distTo[v];  }
```

```
public Iterable<DirectedEdge> pathTo(int v)
{
   Stack<DirectedEdge> path = new Stack<DirectedEdge>();
   for (DirectedEdge e = edgeTo[v]; e != null; e = edgeTo[e.from()])
      path.push(e);
   return path;
}
```

Edge relaxation

Relax edge $e = v \rightarrow w$.

- **distTo[v]** is length of shortest known path from s to v.
- **distTo[w]** is length of shortest known path from s to w.
- **edgeTo[w]** is last edge on shortest known path from s to w.
- If $e = v \rightarrow w$ gives shorter path to w through v, update **distTo[w]** and **edgeTo[w]**.




```
private void relax(DirectedEdge e)
{
   int v = e.from(), w = e.to();
   if (distTo[w] > distTo[v] + e.weight())
   {
       distTo[w] = distTo[v] + e.weight();
       edgeTo[w] = e;
   }
}
```

Shortest-paths optimality conditions

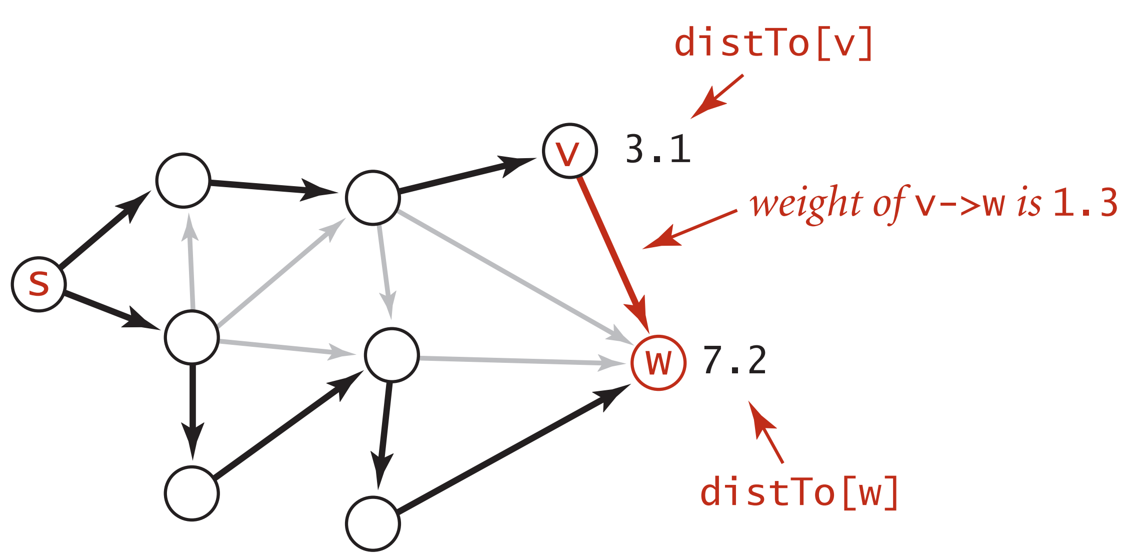
Proposition. Let G be an edge-weighted digraph.

Then **`distTo[]`** are the shortest path distances from s iff:

- For each vertex v, **`distTo[v]`** is the length of some path from s to v.
- For each edge $e = v \rightarrow w$, **`distTo[w] ≤ distTo[v] + e.weight()`**.

Pf. $\Leftarrow$ [necessary]

- Suppose that **`distTo[w] > distTo[v] + e.weight()`** for some edge $e = v \rightarrow w$.
- Then, e gives a path from s to w (through v) of length less than **`distTo[w]`**.



Shortest-paths optimality conditions

Proposition. Let G be an edge-weighted digraph.

Then `distTo[]` are the shortest path distances from s iff:

- For each vertex v, `distTo[v]` is the length of some path from s to v.
- For each edge $e = v \rightarrow w$, `distTo[w] ≤ distTo[v] + e.weight()`.

Pf. $\Rightarrow$ [sufficient]

- Suppose that $s = v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \ldots \rightarrow v_k = w$ is a shortest path from s to w.
- Then,

$$
\begin{aligned}
\texttt{distTo}[v_k] &\le \texttt{distTo}[v_{k-1}] + e_k\texttt{.weight()} \\
\texttt{distTo}[v_{k-1}] &\le \texttt{distTo}[v_{k-2}] + e_{k-1}\texttt{.weight()} \\
&\;\;\ldots \\
\texttt{distTo}[v_1] &\le \texttt{distTo}[v_0] + e_1\texttt{.weight()}
\end{aligned}
$$

e_i = i^{th} edge on shortest path from s to w

- Collapsing these inequalities and eliminate $\texttt{distTo}[v_0] = \texttt{distTo[s]} = 0$:

$$\underbrace{\texttt{distTo[w]}}_{\text{weight of some path from s to w}} = \texttt{distTo}[v_k] \le \underbrace{e_k\texttt{.weight()} + e_{k-1}\texttt{.weight()} + \ldots + e_1\texttt{.weight()}}_{\text{weight of shortest path from s to w}}$$

- Thus, `distTo[w]` is the weight of shortest path to w. ▪

Generic shortest-paths algorithm

Generic algorithm (to compute SPT from s)

Initialize distTo[s] = 0 and distTo[v] = ∞ for all other vertices.

Repeat until optimality conditions are satisfied:

- **Relax any edge.**

Proposition. Generic algorithm computes SPT from s. ← assuming SPT exists

Pf sketch.

- Throughout algorithm, `distTo[v]` is the length of a simple path from s to v and `edgeTo[v]` is last edge on path.
- Each successful relaxation decreases `distTo[v]` for some v.
- The entry `distTo[v]` can decrease at most a finite number of times. ▪

Generic shortest-paths algorithm

Generic algorithm (to compute SPT from s)

Initialize distTo[s] = 0 and distTo[v] = ∞ for all other vertices.

Repeat until optimality conditions are satisfied:

- **Relax any edge.**

Efficient implementations. How to choose which edge to relax?

Ex 1. Dijkstra's algorithm (nonnegative weights).

Ex 2. Topological sort algorithm (no directed cycles).

Ex 3. Bellman-Ford algorithm (no negative cycles).

Shortest Paths

- edge-weighted digraph API
- shortest-paths properties
- Dijkstra's algorithm
- edge-weighted DAGs
- negative weights

Edsger W. Dijkstra: select quotes

" Do only what only you can do. "

" In their capacity as a tool, computers will be but a ripple on the surface of our culture. In their capacity as intellectual challenge, they are without precedent in the cultural history of mankind. "

" The use of COBOL cripples the mind; its teaching should, therefore, be regarded as a criminal offence. "

" It is practically impossible to teach good programming to students that have had a prior exposure to BASIC: as potential programmers they are mentally mutilated beyond hope of regeneration. "

" APL is a mistake, carried through to perfection. It is the language of the future for the programming techniques of the past: it creates a new generation of coding bums. "

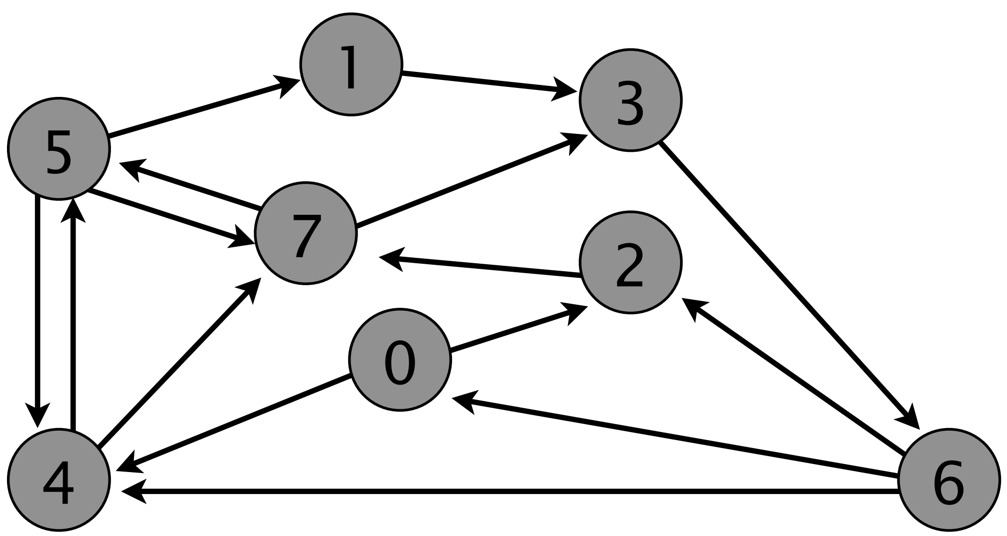
Edsger W. Dijkstra
Turing award 1972

Edsger W. Dijkstra: select quotes

Dijkstra's algorithm

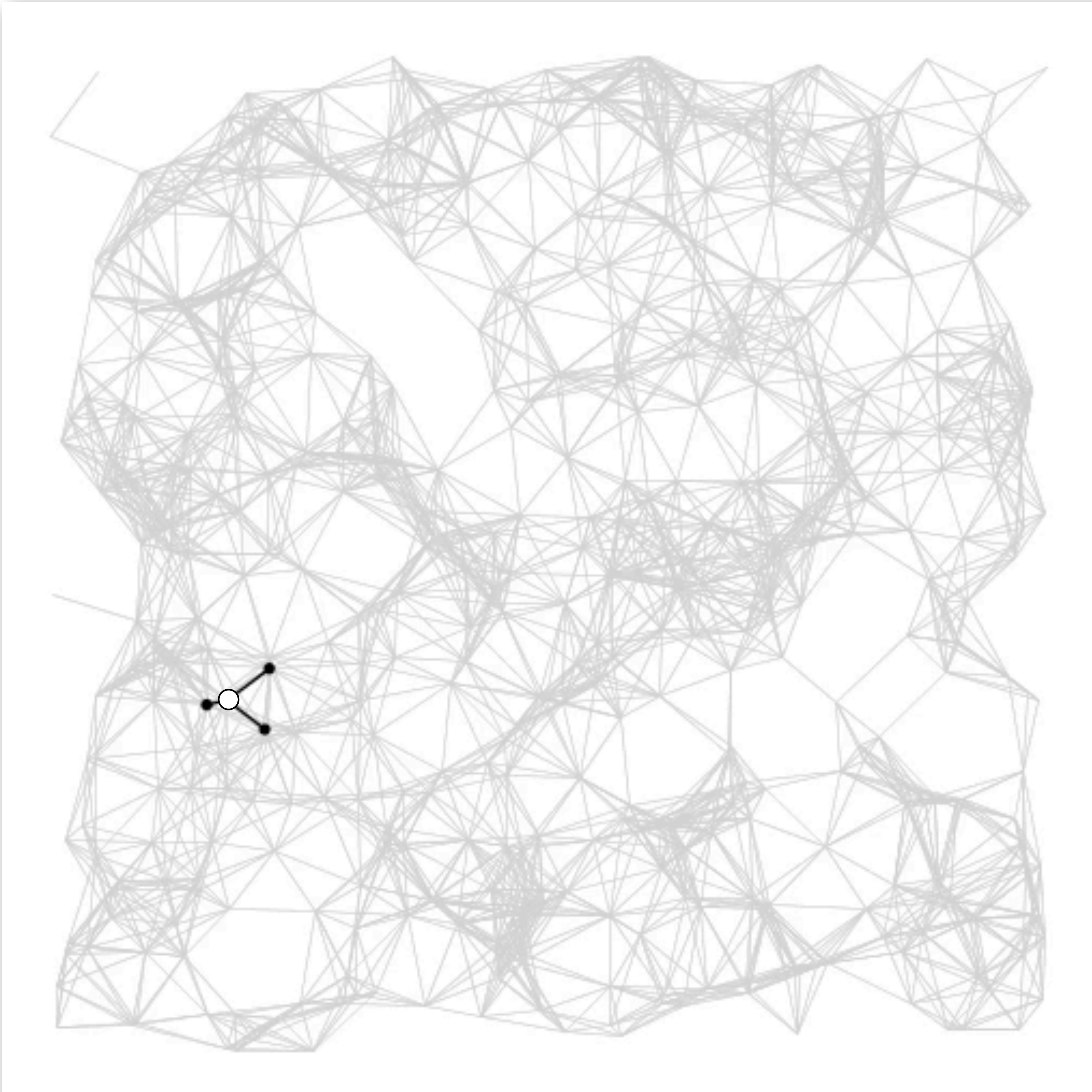
- Consider vertices in increasing order of distance from s (non-tree vertex with the lowest **`distTo[]`** value).
- Add vertex to tree and relax all edges incident from that vertex.

```
4->5  0.35
5->4  0.35
4->7  0.37
5->7  0.28
7->5  0.28
5->1  0.32
0->4  0.38
0->2  0.26
7->3  0.39
1->3  0.29
2->7  0.34
6->2  0.40
3->6  0.52
6->0  0.58
6->4  0.93
```

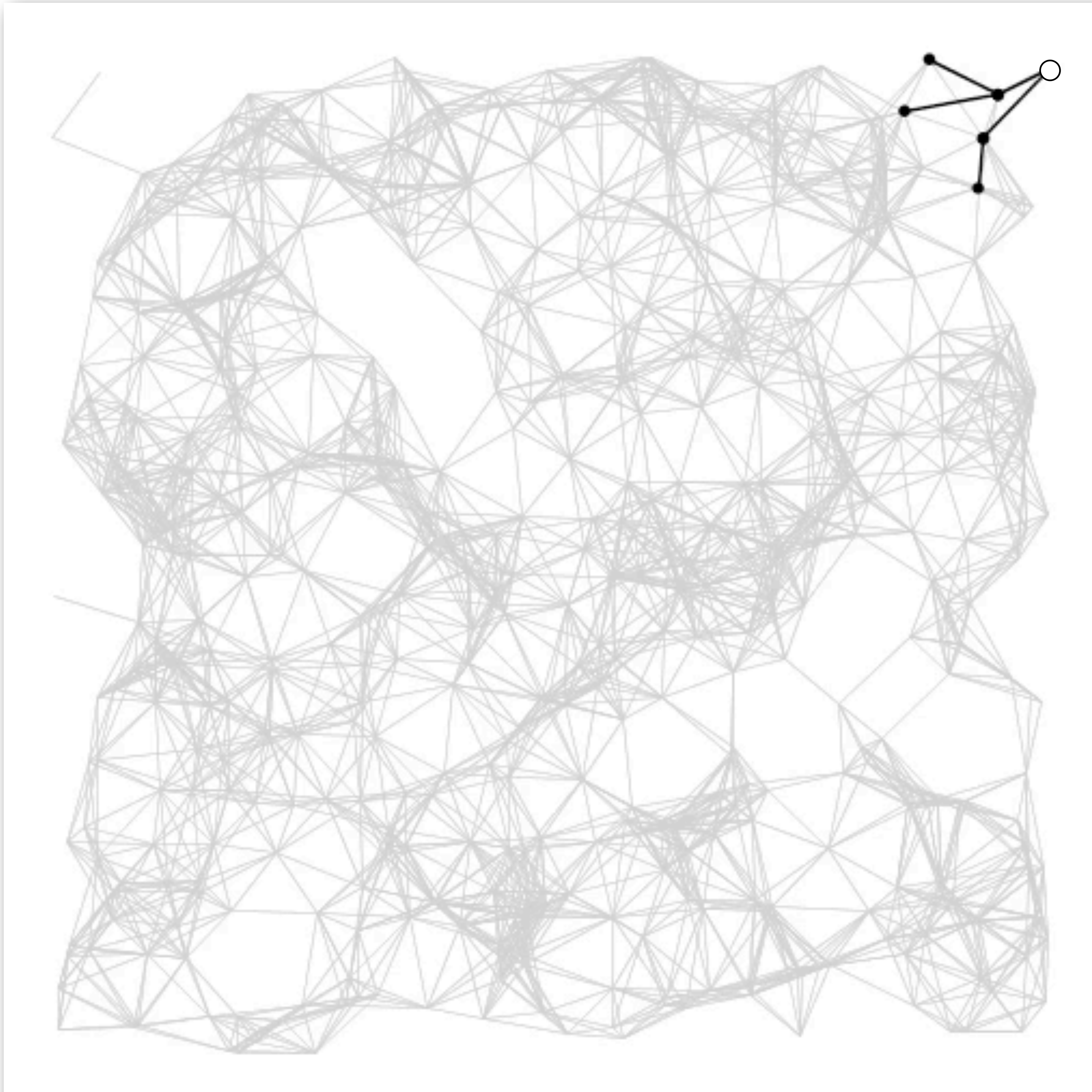


v	distTo[v]	edgeTo[v]
0	0.00	-
1		
2		
3		
4		
5		
6		
7		

Dijkstra's algorithm visualization

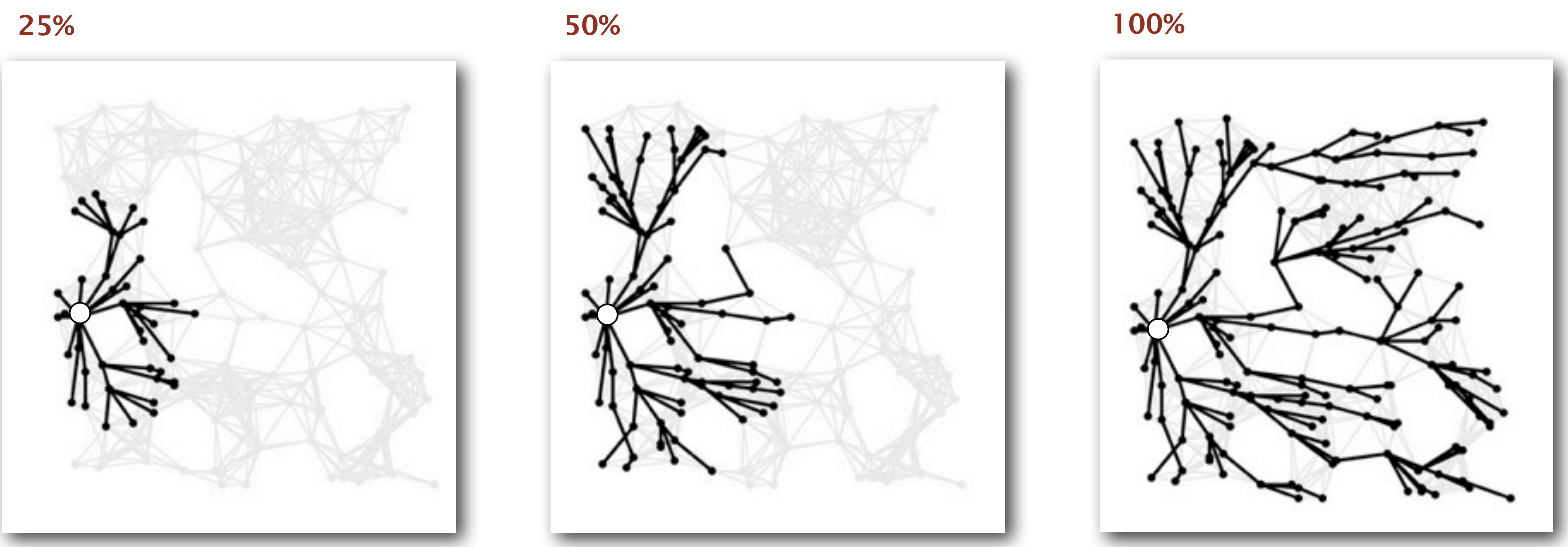


Dijkstra's algorithm visualization



Shortest path trees

- Consider vertices in increasing order of distance from s (non-tree vertex with the lowest **`distTo[]`** value).
- Add vertex to tree and relax all edges incident from that vertex.



Dijkstra's algorithm: correctness proof

Proposition. Dijkstra's algorithm computes SPT in any edge-weighted digraph with nonnegative weights.

Pf.

- Each edge $e = v \rightarrow w$ is relaxed exactly once (when v is relaxed), leaving **`distTo[w] ≤ distTo[v] + e.weight()`**.
- Inequality holds until algorithm terminates because:
  - **`distTo[w]`** cannot increase ← **`distTo[]`** values are monotone decreasing
  - **`distTo[v]`** will not change ← edge weights are nonnegative and we choose lowest **`distTo[]`** value at each step
- Thus, upon termination, shortest-paths optimality conditions hold. ▪

Dijkstra's algorithm: Java implementation

```
public class DijkstaSP
{
   private DirectedEdge[] edgeTo;
   private double[] distTo;
   private IndexMinPQ<Double> pq;

   public DijkstraSP(EdgeWeightedDigraph G, int s)
   {
      edgeTo = new DirectedEdge[G.V()];
      distTo = new double[G.V()];
      pq = new IndexMinPQ<Double>(G.V());

      for (int v = 0; v < G.V(); v++)
         distTo[v] = Double.POSITIVE_INFINITY;
      distTo[s] = 0.0;

      pq.insert(s, 0.0);
      while (pq.isEmpty())
      {
          int v = pq.delMin();
          for (DirectedEdge e : G.adj(v))
             relax(e);
      }
    }
 }
```

relax vertices in order of distance from s

Dijkstra's algorithm: Java implementation

```
private void relax(DirectedEdge e)
{
   int v = e.from(), w = e.to();
   if (distTo[w] > distTo[v] + e.weight())
   {
       distTo[w] = distTo[v] + e.weight();
       edgeTo[w] = e;
       if (pq.contains(w)) pq.decreaseKey(w, distTo[w]);
       else                pq.insert     (w, distTo[w]);
   }
}
```

update PQ

Dijkstra's algorithm: which priority queue?

Depends on PQ implementation: V insert, V delete-min, E decrease-key.

PQ implementation	insert	delete-min	decrease-key	total
array	1	V	1	V^2
binary heap	$\log V$	$\log V$	$\log V$	$E \log V$
d-way heap (Johnson 1975)	$d \log_d V$	$d \log_d V$	$\log_d V$	$E \log_{E/V} V$
Fibonacci heap (Fredman-Tarjan 1984)	1 †	$\log V$ †	1 †	$E + V \log V$

† amortized

Bottom line.

- Array implementation optimal for dense graphs.
- Binary heap much faster for sparse graphs.
- d-way heap worth the trouble in performance-critical situations.
- Fibonacci heap best in theory, but not worth implementing.

Priority-first search

Insight. Four of our graph-search methods are the same algorithm!

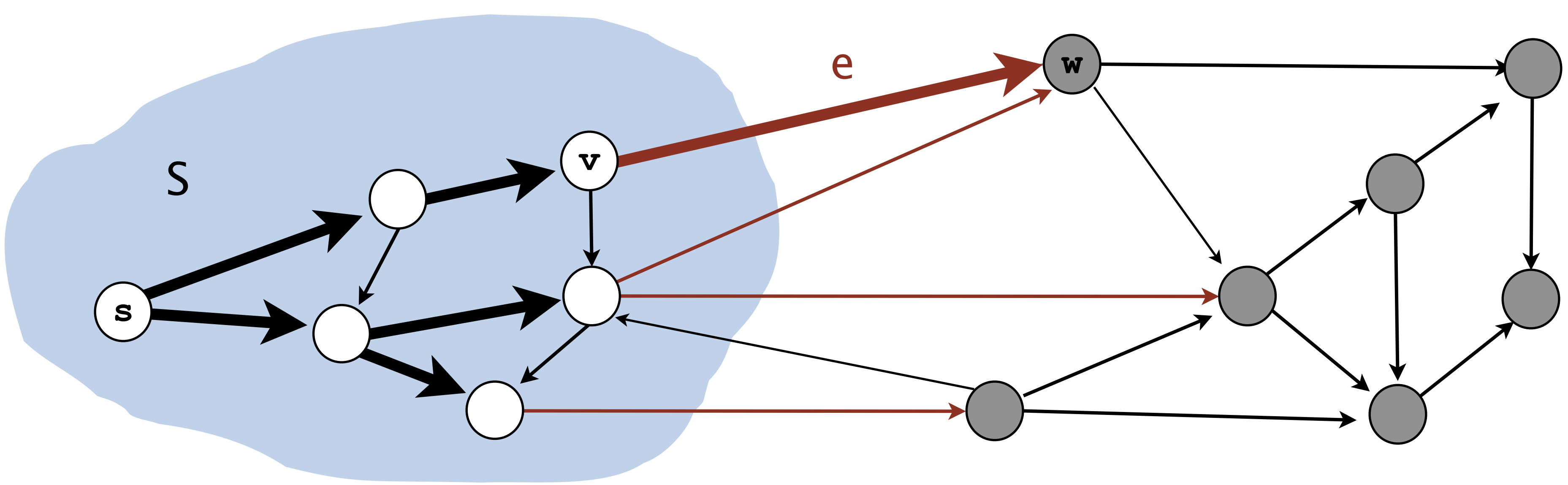
- Maintain a set of explored vertices S.
- Grow S by exploring edges with exactly one endpoint leaving S.

DFS. Take edge from vertex which was discovered most recently.

BFS. Take edge from vertex which was discovered least recently.

Prim. Take edge of minimum weight.

Dijkstra. Take edge to vertex that is closest to S.



Challenge. Express this insight in reusable Java code.

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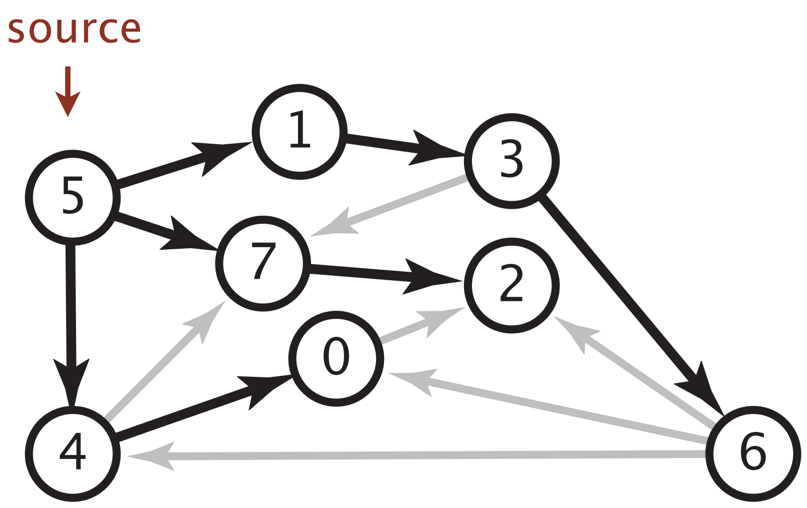
Acyclic edge-weighted digraphs

Q. Suppose that an edge-weighted digraph has no directed cycles.
Is it easier to find shortest paths than in a general digraph?

A. Yes!

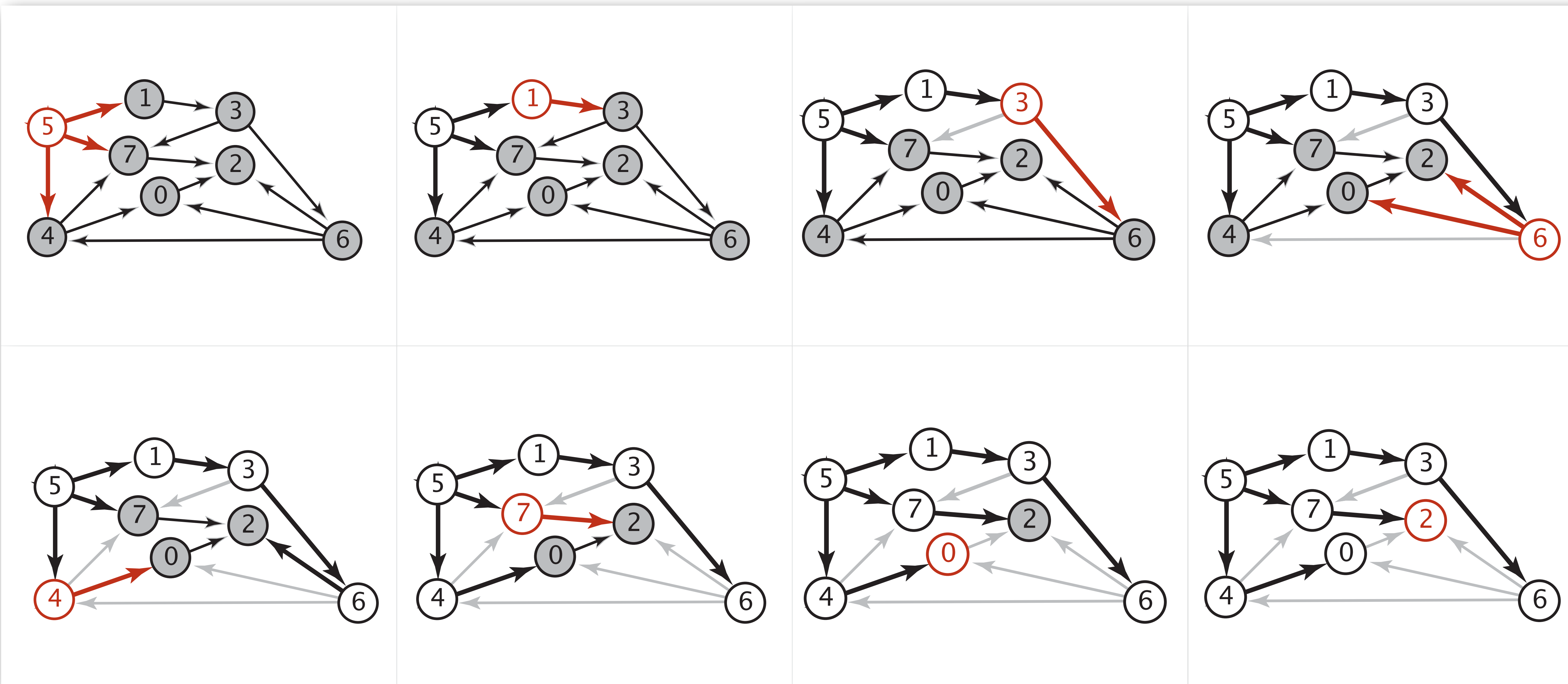
5->4	0.35
4->7	0.37
5->7	0.28
5->1	0.32
4->0	0.38
0->2	0.26
3->7	0.39
1->3	0.29
7->2	0.34
6->2	0.40
3->6	0.52
6->0	0.58
6->4	0.93



Shortest paths in edge-weighted DAGs

Topological sort algorithm.

- Consider vertices in topologically order.
- Relax all edges incident from vertex.



topological order: 5 1 3 6 4 7 0 2

Shortest paths in edge-weighted DAGs

```
public class AcyclicSP
{
   private DirectedEdge[] edgeTo;
   private double[] distTo;

   public AcyclicSP(EdgeWeightedDigraph G, int s)
   {
      edgeTo = new DirectedEdge[G.V()];
      distTo = new double[G.V()];

      for (int v = 0; v < G.V(); v++)
         distTo[v] = Double.POSITIVE_INFINITY;
      distTo[s] = 0.0;

      Topological topological = new Topological(G);
      for (int v : topological.order())
         for (DirectedEdge e : G.adj(v))
            relax(e);
    }
 }
```

topological order

Shortest paths in edge-weighted DAGs

Topological sort algorithm.

- Consider vertices in topologically order.
- Relax all edges incident from vertex.

Proposition. Topological sort algorithm computes SPT in any edge-weighted DAG in time proportional to $E + V$.

Pf.

- Each edge $e = v \rightarrow w$ is relaxed exactly once (when v is relaxed), leaving **`distTo[w] ≤ distTo[v] + e.weight()`**.
- Inequality holds until algorithm terminates because:
  - **`distTo[w]`** cannot increase ← `distTo[]` values are monotone decreasing
  - **`distTo[v]`** will not change ← because of topological order, no edge pointing to v will be relaxed after v is relaxed
- Thus, upon termination, shortest-paths optimality conditions hold. ∎

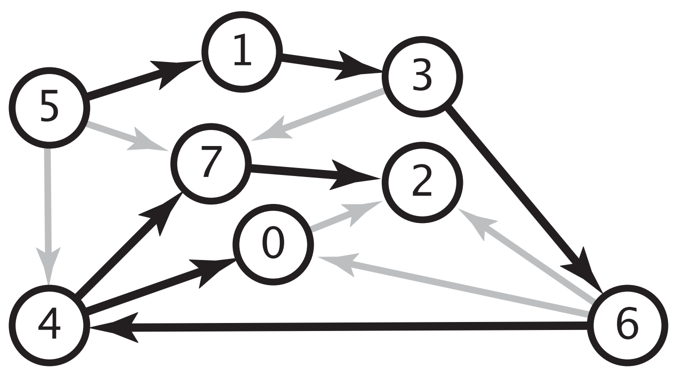
Longest paths in edge-weighted DAGs

Formulate as a shortest paths problem in edge-weighted DAGs.

- Negate all weights.
- Find shortest paths.
- Negate weights in result.

equivalent: reverse sense of equality in `relax()`

longest paths input		shortest paths input	
5->4	0.35	5->4	-0.35
4->7	0.37	4->7	-0.37
5->7	0.28	5->7	-0.28
5->1	0.32	5->1	-0.32
4->0	0.38	4->0	-0.38
0->2	0.26	0->2	-0.26
3->7	0.39	3->7	-0.39
1->3	0.29	1->3	-0.29
7->2	0.34	7->2	-0.34
6->2	0.40	6->2	-0.40
3->6	0.52	3->6	-0.52
6->0	0.58	6->0	-0.58
6->4	0.93	6->4	-0.93



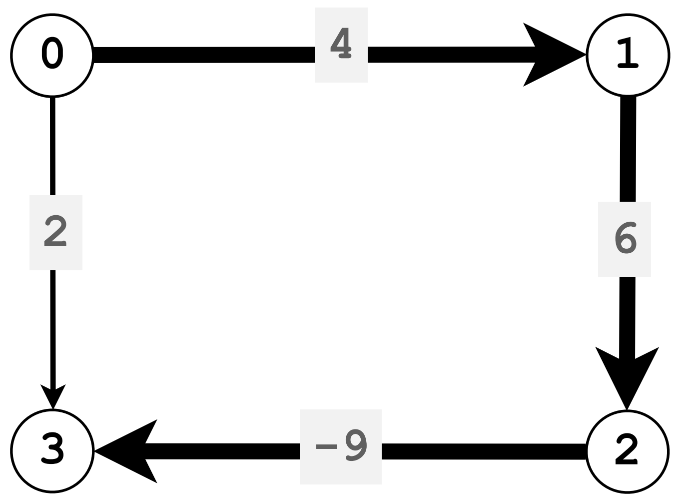
Key point. Topological sort algorithm works even with negative edge weights.

Shortest Paths

- edge-weighted digraph API
- shortest-paths properties
- Dijkstra's algorithm
- edge-weighted DAGs
- negative weights

Shortest paths with negative weights: failed attempts

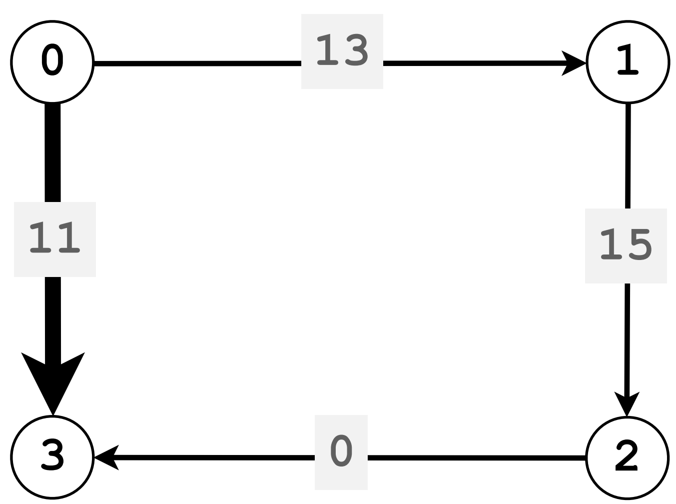
Dijkstra. Doesn't work with negative edge weights.



Dijkstra selects vertex 3 immediately after 0.

But shortest path from 0 to 3 is 0→1→2→3.

Re-weighting. Add a constant to every edge weight doesn't work.



Adding 9 to each edge weight changes the shortest path from 0→1→2→3 to 0→3.

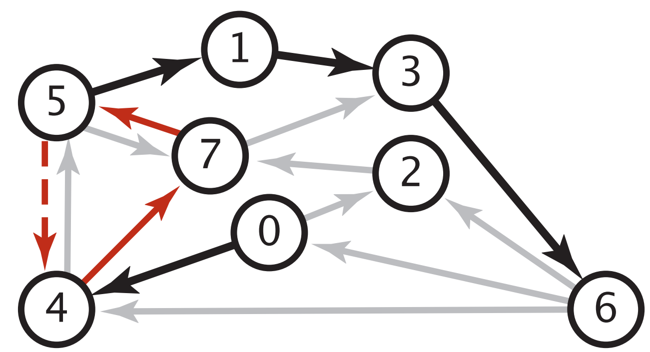
Bad news. Need a different algorithm.

Negative cycles

Def. A negative cycle is a directed cycle whose sum of edge weights is negative.

digraph

4->5	0.35
5->4	-0.66
4->7	0.37
5->7	0.28
7->5	0.28
5->1	0.32
0->4	0.38
0->2	0.26
7->3	0.39
1->3	0.29
2->7	0.34
6->2	0.40
3->6	0.52
6->0	0.58
6->4	0.93



negative cycle (-0.66 + 0.37 + 0.28)

5->4->7->5

shortest path from 0 to 6

0->4->7->5->4->7->5...->1->3->6

Proposition. A SPT exists iff no negative cycles.

assuming all vertices reachable from s

Bellman-Ford algorithm

Observation. If **`distTo[v]`** does not change during phase i, no need to relax any edge incident from v in phase $i+1$.

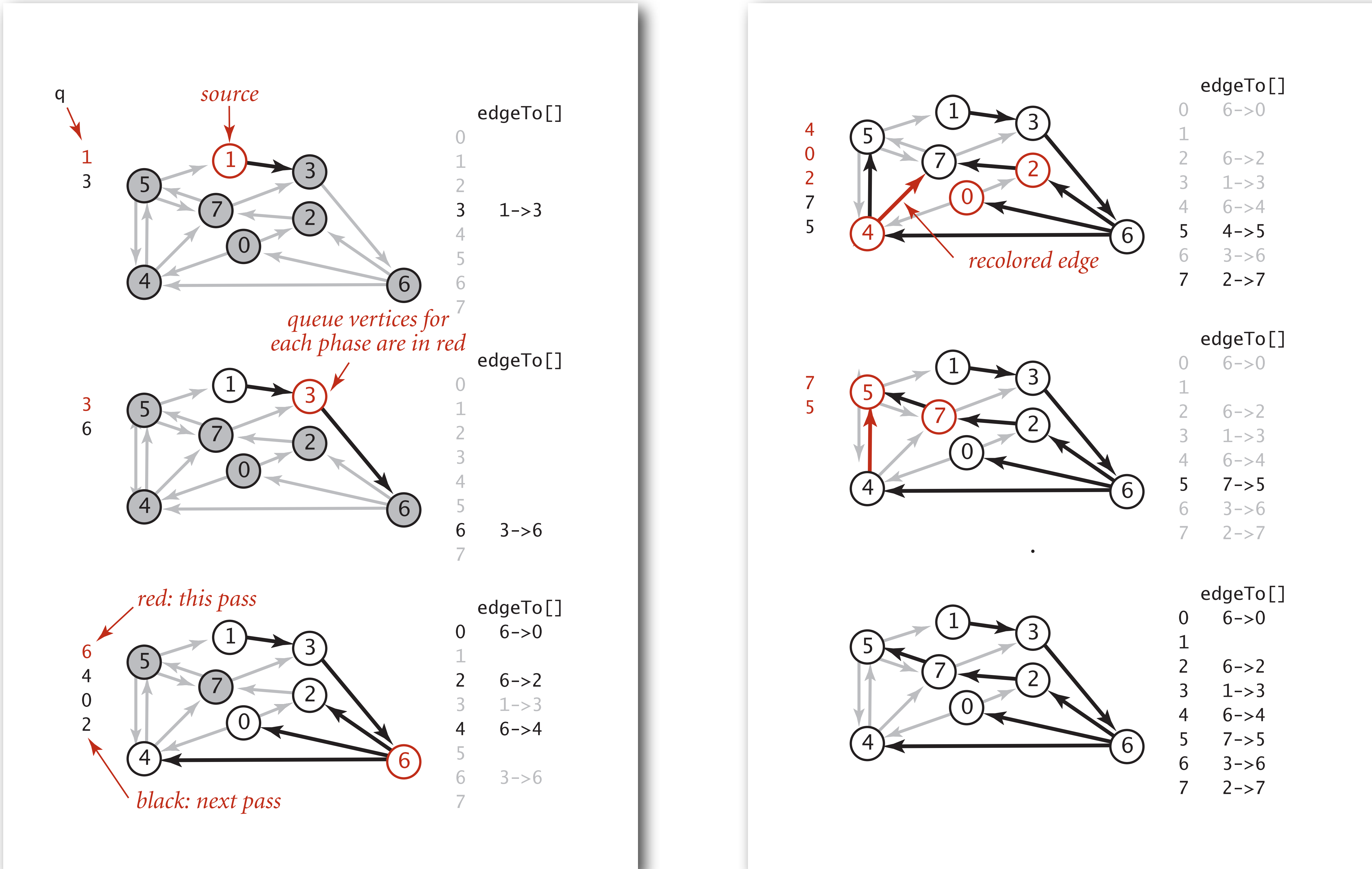
FIFO implementation. Maintain queue of vertices whose **`distTo[]`** changed.

be careful to keep at most one copy of each vertex on queue (why?)

Overall effect.

- The running time is still proportional to $E \times V$ in worst case.
- But much faster than that in practice.

Bellman-Ford algorithm trace



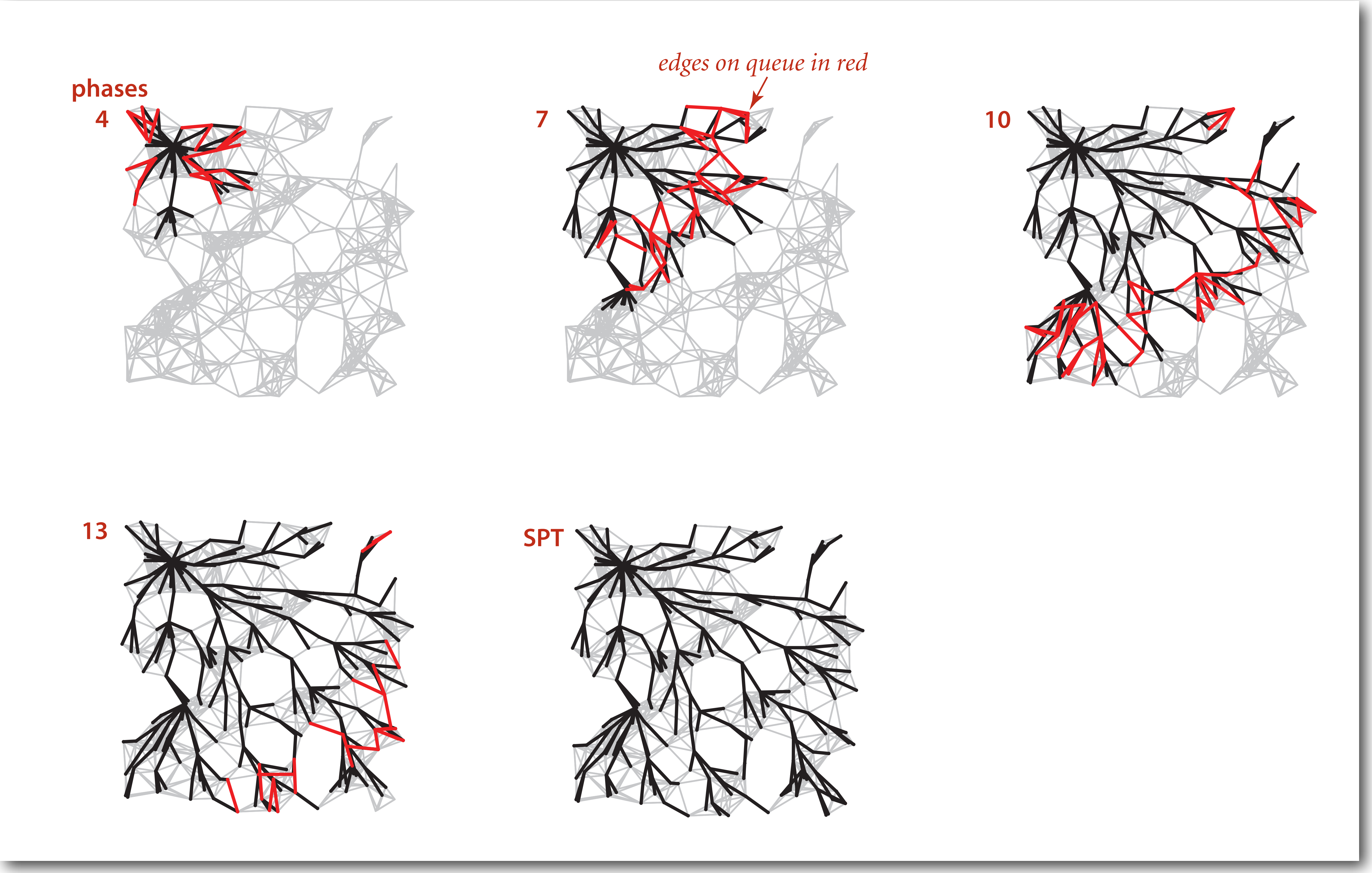
Bellman-Ford algorithm

```
public class BellmanFordSP
{
   private double[] distTo;
   private DirectedEdge[] edgeTo;
   private int[] onQ;
   private Queue<Integer> queue;

   public BellmanFordSPT(EdgeWeightedDigraph G, int s)
   {
      distTo = new double[G.V()];
      edgeTo = new DirectedEdge[G.V()];
      onq    = new int[G.V()];
      queue  = new Queue<Integer>();

      for (int v = 0; v < V; v++)
         distTo[v] = Double.POSITIVE_INFINITY;
      distTo[s] = 0.0;

      queue.enqueue(s);
      while (!queue.isEmpty())
      {
         int v = queue.dequeue();
         onQ[v] = false;
         for (DirectedEdge e : G.adj(v))
            relax(e);
      }
   }
}
```

queue of vertices whose `distTo[]` value changes

```
private void relax(DirectedEdge e)
{
   int v = e.from(), w = e.to();
   if (distTo[w] > distTo[v] + e.weight())
   {
       distTo[w] = distTo[v] + e.weight();
       edgeTo[w] = e;
       if (!onQ[w])
       {
          q.enqueue(w);
          onQ[w] = true;
       }
   }
}
```

Bellman-Ford algorithm visualization



Single source shortest-paths implementation: cost summary

algorithm	restriction	typical case	worst case	extra space
topological sort	no directed cycles	E + V	E + V	V
Dijkstra (binary heap)	no negative weights	E log V	E log V	V
dynamic programming	no negative cycles	E V	E V	V
Bellman-Ford		E + V	E V	V

Remark 1. Directed cycles make the problem harder.

Remark 2. Negative weights make the problem harder.

Remark 3. Negative cycles makes the problem intractable.

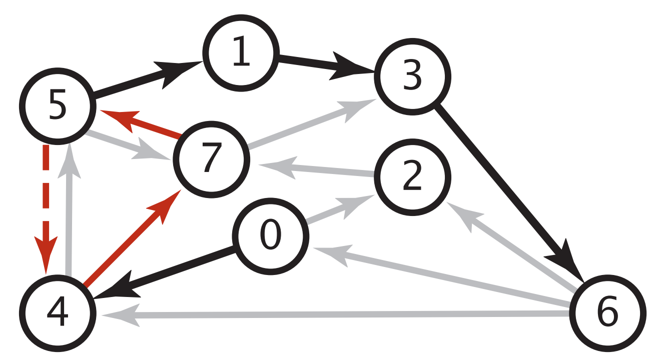
Finding a negative cycle

Negative cycle. Add two method to the API for **SP**.

`boolean`	`hasNegativeCycle()`	*is there a negative cycle?*
`Iterable <DirectedEdge>`	`negativeCycle()`	*negative cycle reachable from s*

digraph

```
4->5   0.35
5->4  -0.66
4->7   0.37
5->7   0.28
7->5   0.28
5->1   0.32
0->4   0.38
0->2   0.26
7->3   0.39
1->3   0.29
2->7   0.34
6->2   0.40
3->6   0.52
6->0   0.58
6->4   0.93
```

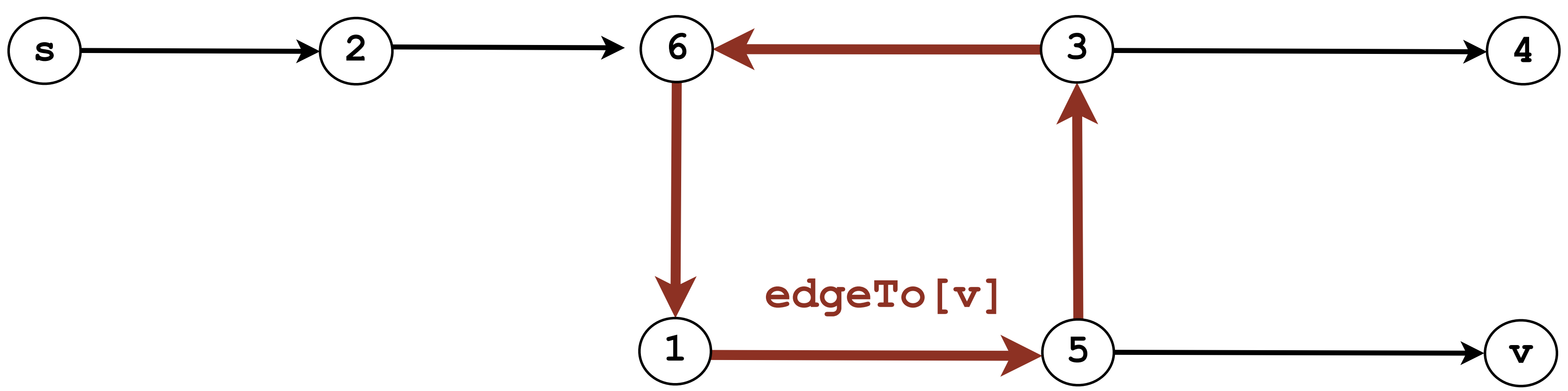


negative cycle (-0.66 + 0.37 + 0.28)

5->4->7->5

Finding a negative cycle

Observation. If there is a negative cycle, Bellman-Ford gets stuck in loop, updating **`distTo[]`** and **`edgeTo[]`** entries of vertices in the cycle.



Proposition. If any vertex v is updated in phase V, there exists a negative cycle (and can trace back **`edgeTo[v]`** entries to find it).

In practice. Check for negative cycles more frequently.

Negative cycle application: arbitrage detection

Problem. Given table of exchange rates, is there an arbitrage opportunity?

	USD	EUR	GBP	CHF	CAD
USD	1	0.741	0.657	1.061	1.011
EUR	1.350	1	0.888	1.433	1.366
GBP	1.521	1.126	1	1.614	1.538
CHF	0.943	0.698	0.620	1	0.953
CAD	0.995	0.732	0.650	1.049	1

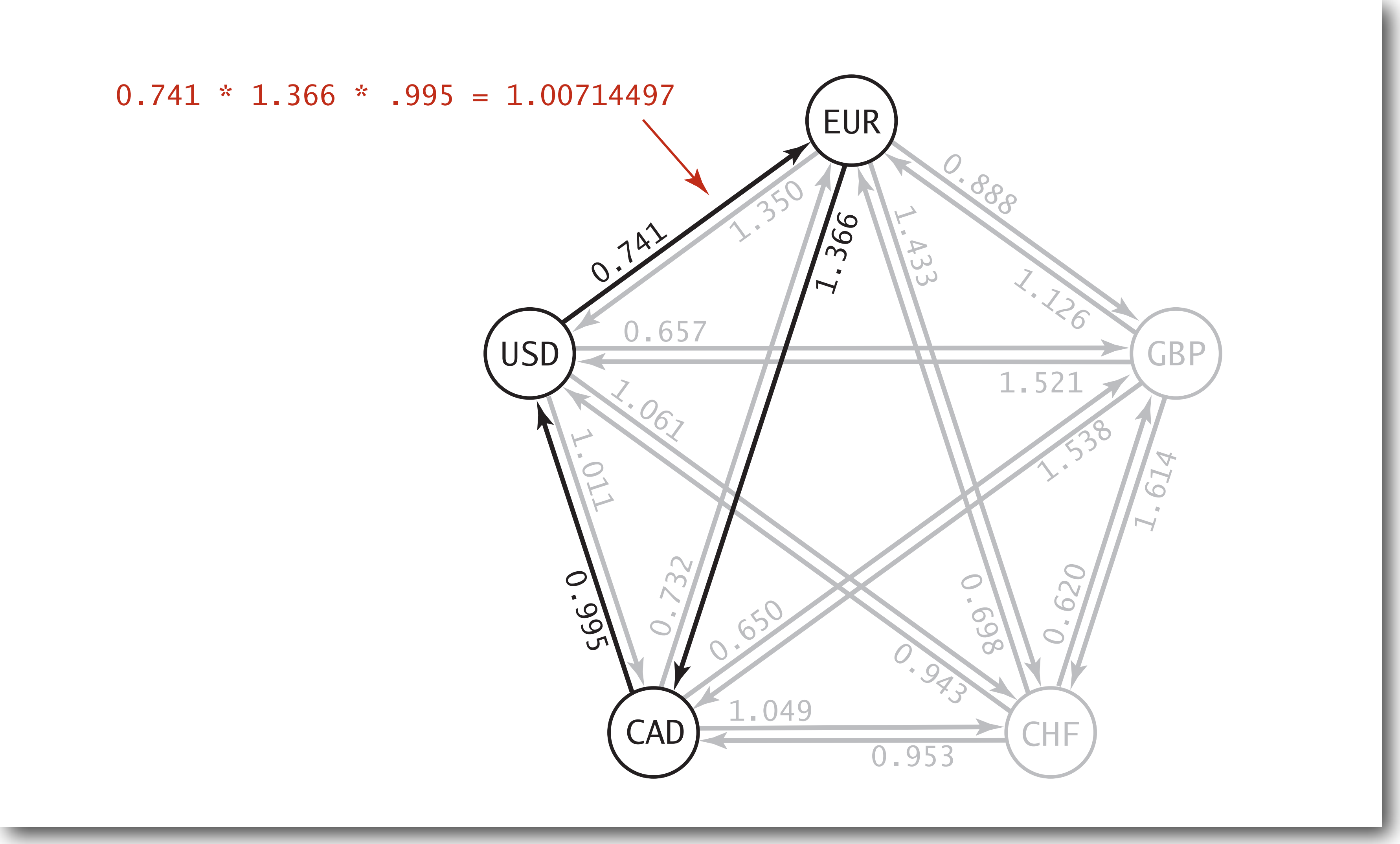
Ex. \$1,000 $\Rightarrow$ 741 Euros $\Rightarrow$ 1,012.206 Canadian dollars $\Rightarrow$ \$1,007.14497.

$1000 \times 0.741 \times 1.366 \times 0.995 = 1007.14497$

Negative cycle application: arbitrage detection

Currency exchange graph.

- Vertex = currency.
- Edge = transaction, with weight equal to exchange rate.
- Find a directed cycle whose product of edge weights is > 1.

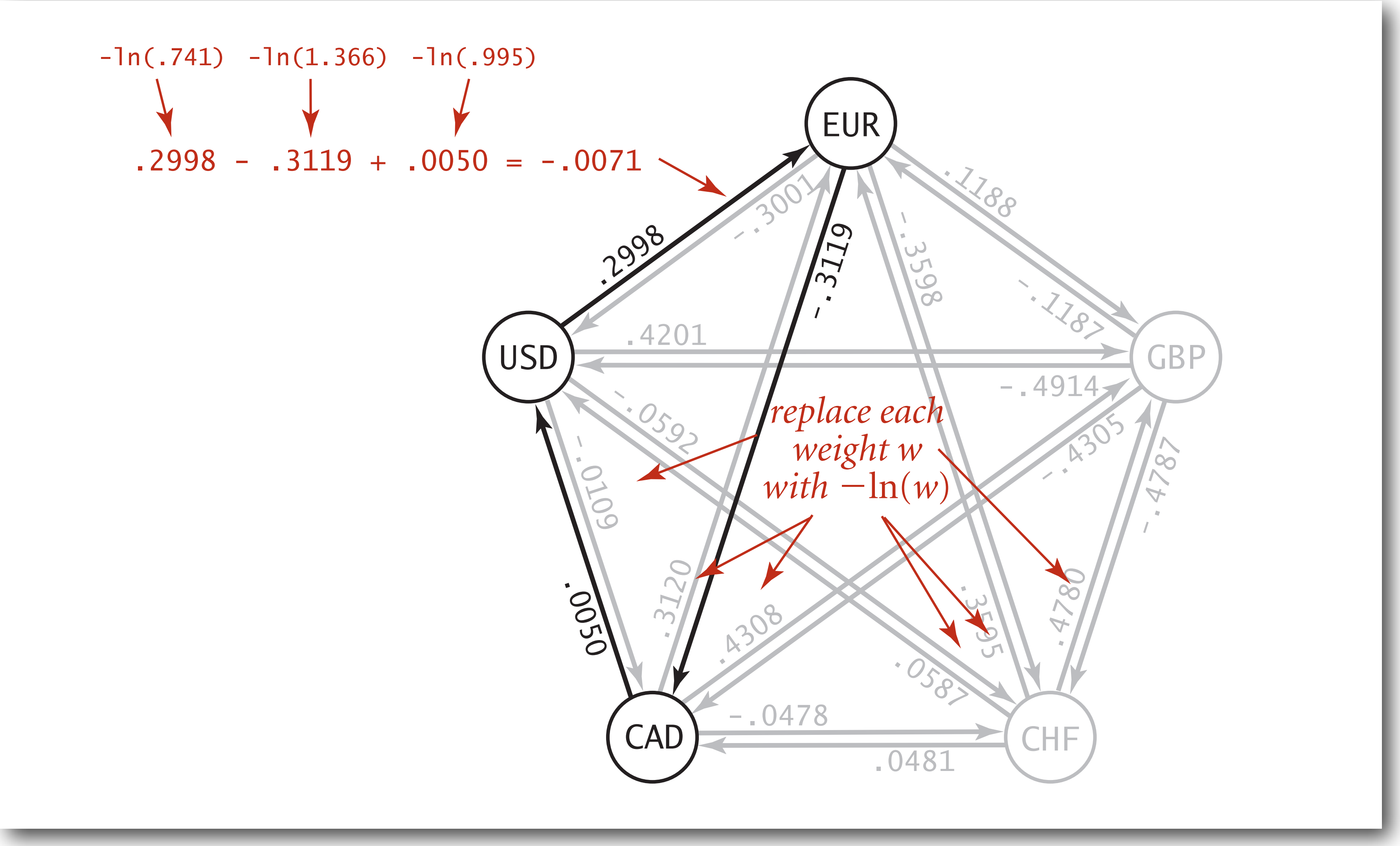


Challenge. Express as a negative cycle detection problem.

Negative cycle application: arbitrage detection

Model as a negative cycle detection problem by taking logs.

- Let weight of edge $v \rightarrow w$ be $-\ ln$ (exchange rate from currency v to w).
- Multiplication turns to addition; > 1 turns to < 0.
- Find a directed cycle whose sum of edge weights is < 0 (negative cycle).



Remark. Fastest algorithm is extraordinarily valuable!

Shortest paths summary

Dijkstra's algorithm.

- Nearly linear-time when weights are nonnegative.
- Generalization encompasses DFS, BFS, and Prim.

Acyclic edge-weighted digraphs.

- Arise in applications.
- Faster than Dijkstra's algorithm.
- Negative weights are no problem.

Negative weights and negative cycles.

- Arise in applications.
- If no negative cycles, can find shortest paths via Bellman-Ford.
- If negative cycles, can find one via Bellman-Ford.

Shortest-paths is a broadly useful problem-solving model.