Link State Routing

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Outline

- Link State Approach to Routing
- Finding Links: Hello Protocol
- Building a Map: Flooding Protocol
- Healing after Partitions: Bringing up Adjacencies
- Finding Routes: Dijkstra's Shortest-Path-First Algorithm
- Properties of Link State Routing

Link State Approach to Routing

- Finding shortest paths in graph is classic theory problem
- Classic centralized single-source shortest paths algorithm: Dijkstra's Algorithm
  - requires map of entire network
- Link State Routing:
  - push a copy of whole network map to every router
  - each router learns link state database
  - each router runs Dijkstra's algorithm locally

Finding Links: Hello Protocol

- Each router configured to know its interfaces
- On each interface, every period P transmit a hello packet containing
  - sender's ID
  - list of neighbors from which sender has heard hello during period D
  - D > P (*e.g.*, D = 3P)
- Link becomes up if have received hello containing own ID on it in last period D
- Link becomes down if no such hello received in last period D
- Screens out unidirectional links

Building a Map: Flooding Protocol

- Whenever node becomes up or becomes down, flood announcement to whole network
  - two link endpoint addresses
  - metric for link (configured by administrator)
  - sequence number
- Sequence number stored in link state database; incremented on every changed announcement
  - prevents old link states from overwriting new ones
- Upon receiving new link state message on interface i:

  if link not in database, add it, flood elsewhere

  if link in database, and seqno in message higher than one in database, write into database, flood elsewhere

  if link in database and seqno in message lower than one in database, send link state from database on interface i

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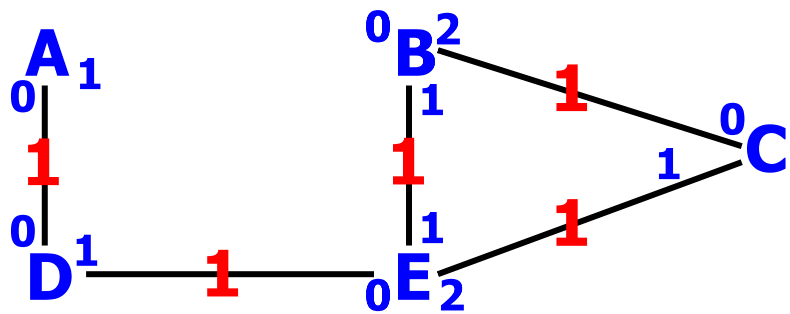
Healing Network Partitions

- Recall example from Distance Vector routing where network partitions
- Consider flooding behavior when partitions heal



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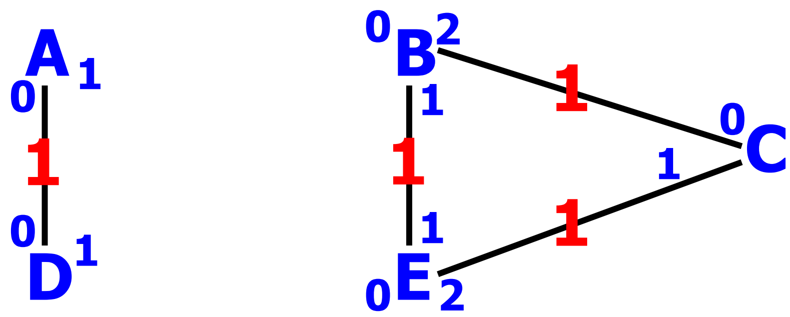

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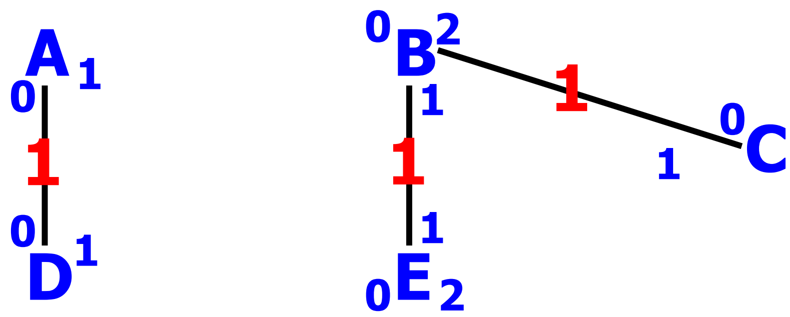

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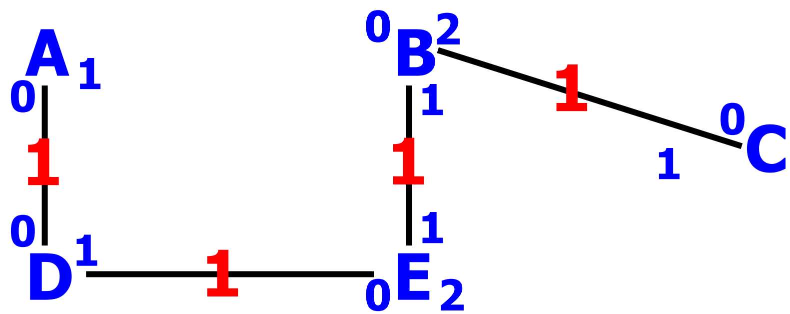
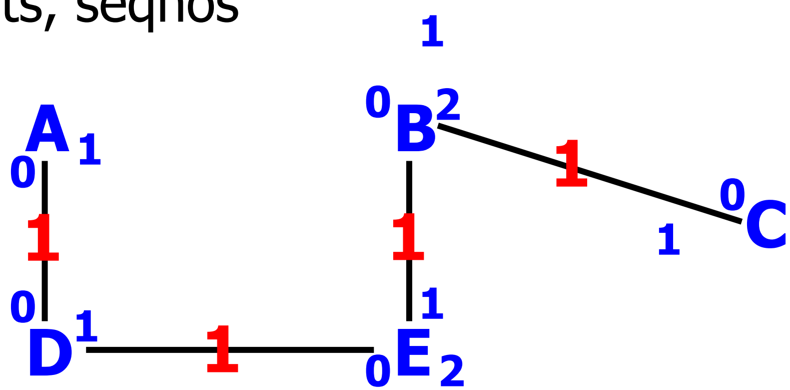


Healing Network Partitions (II)

- D detects link (D, E), floods link state to A
- A and D may still think link (C, E) exists!
- If first time link (D, E) comes up, how will A learn about links (B, E), (B, C)?
- Flooding to report changes only in neighboring links not always sufficient!
- Bringing up adjacencies:
  - when link comes up, routers at ends exchange short summaries (link endpoints, sequence numbers) of their whole databases
  - routers then request missing or newer entries from one another
  - saves bandwidth; real LS database entries contain more than link endpoints, seqnos



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Link State Database → Routing Table

- After flooding each router holds map of entire network graph in memory
- Need to transform network map into routing table
- How: single-source shortest paths algorithm
- Router views itself as source s, all other routers as destinations

Shortest Paths: Definitions

- Each router is a vertex, $v \in V$
- Each link is an edge, $e \in E$, also written (u, v)
- Each link metric an edge weight, $w(u, v)$
- Series of edges is a path, whose cost is sum of edges' weights
- Single-source shortest paths: seek path with least cost from s to all other vertices
- Data structures:
  - $\pi[v]$ is predecessor of v: $\pi[v]$ is vertex before v along shortest path from s to v
  - $d[v]$ is shortest path estimate: least cost found from s to v so far

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Assume all edge weights nonnegative
(Doesn't make sense for a link to have negative cost…)

  - $\pi[v]$ is predecessor of v: $\pi[v]$ is vertex before v along shortest path from s to v
  - $d[v]$ is shortest path estimate: least cost found from s to v so far

Shortest Paths: Initialization

- When we start, we know little:
  - no estimate of cost of any path from s to any other vertex
  - no predecessor of v along shortest path from s to any v

initialize-single-source(V, s)

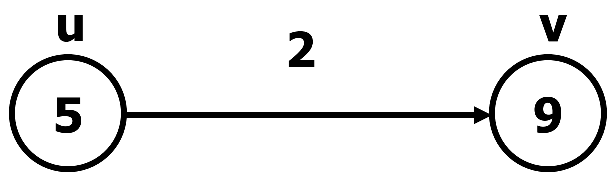
    for each vertex v ∈ V do
        d[v] ← infinity
        π[v] ← NULL
    d[s] = 0

Shortest Paths Building Block: Relaxation

- Relaxation:
  - Suppose we have current estimates d[u], d[v] of shortest path cost from s to u and v
  - Does it reduce cost of shortest path from s to v to reach v via (u, v)?

```
relax(u, v, w)
   if d[v] > d[u] + w(u, v) then
      d[v] ← d[u] + w(u, v)
      π[v] ← u
```

Relaxation: Example



- Suppose
  - d[u] = 5
  - d[v] = 9
  - w(u, v) = 2
- relax(u, v, w) computes:
  - d[v] ?> d[u] + w(u, v)
  - 9 ?> 5 + 2
    - Yes, so reaching v via (u, v) reduces path cost
  - d[v] = d[u] + w(u, v)
  - π[v] = u

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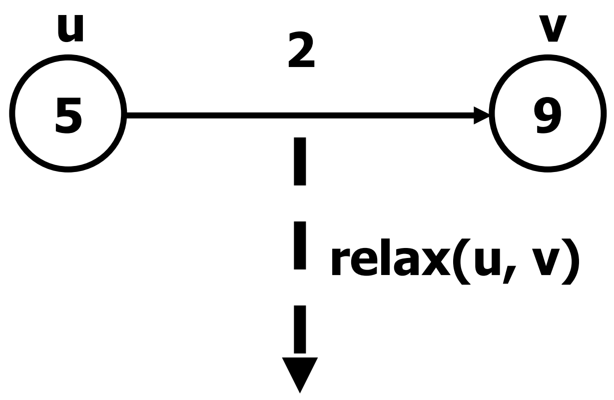

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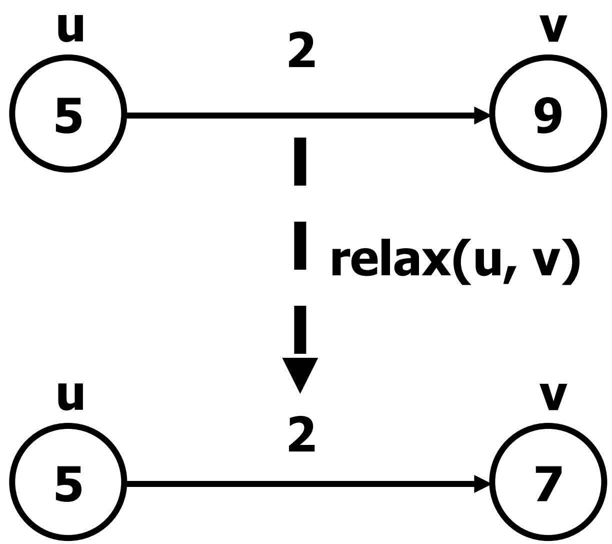

Dijkstra’s Algorithm: Overall Strategy

- Maintain running estimates of costs of shortest paths to all vertices (initially all infinity)
- Keep a set S of vertices that are “finished”; shortest paths to these vertices already found (initially empty)
- Repeatedly pick the unfinished vertex v with least shortest path cost estimate
- Add v to set S
- Relax all edges leaving v

Dijkstra's Algorithm: Overall Strategy

- Maintain running estimates of costs of shortest paths to all vertices (initially all infinity)
- Keep a set S of vertices that are

N.B. only correct for graphs where edge weights nonnegative!

with least shortest path cost estimate

- Add v to set S
- Relax all edges leaving v

Dijkstra’s Algorithm: Pseudocode

```
Dijkstra(V, E, w, s)
    initialize-single-source(V, s)
    S ← ∅
    Q ← V
    while Q ≠ ∅ do
        u ← extract-min(Q)
        S ← S ∪ {u}
        for each vertex v that neighbors u do
            relax(u, v, w)
```

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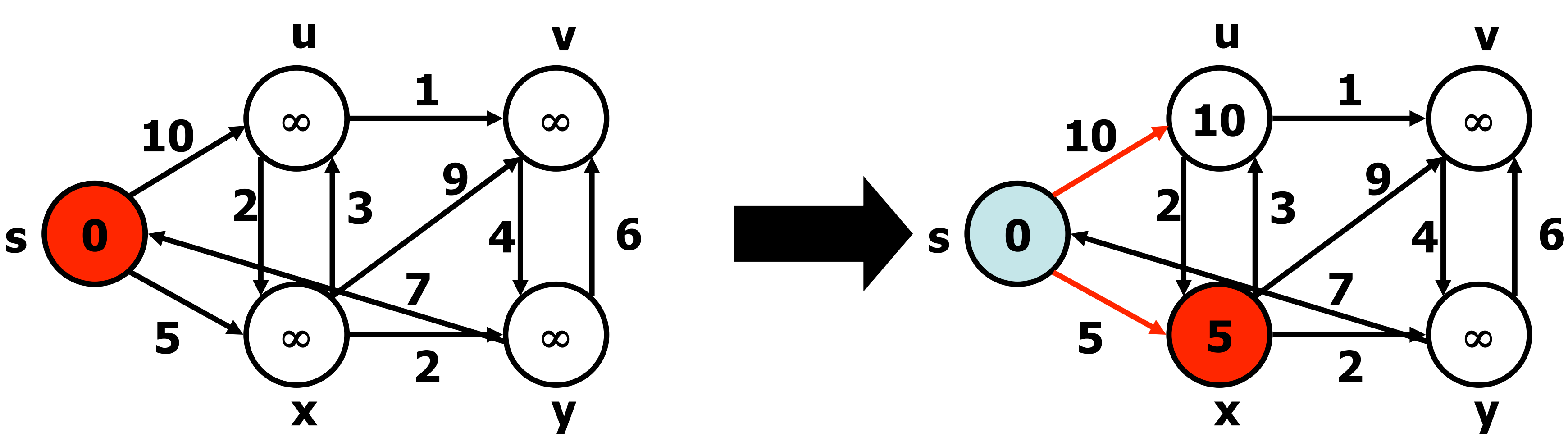
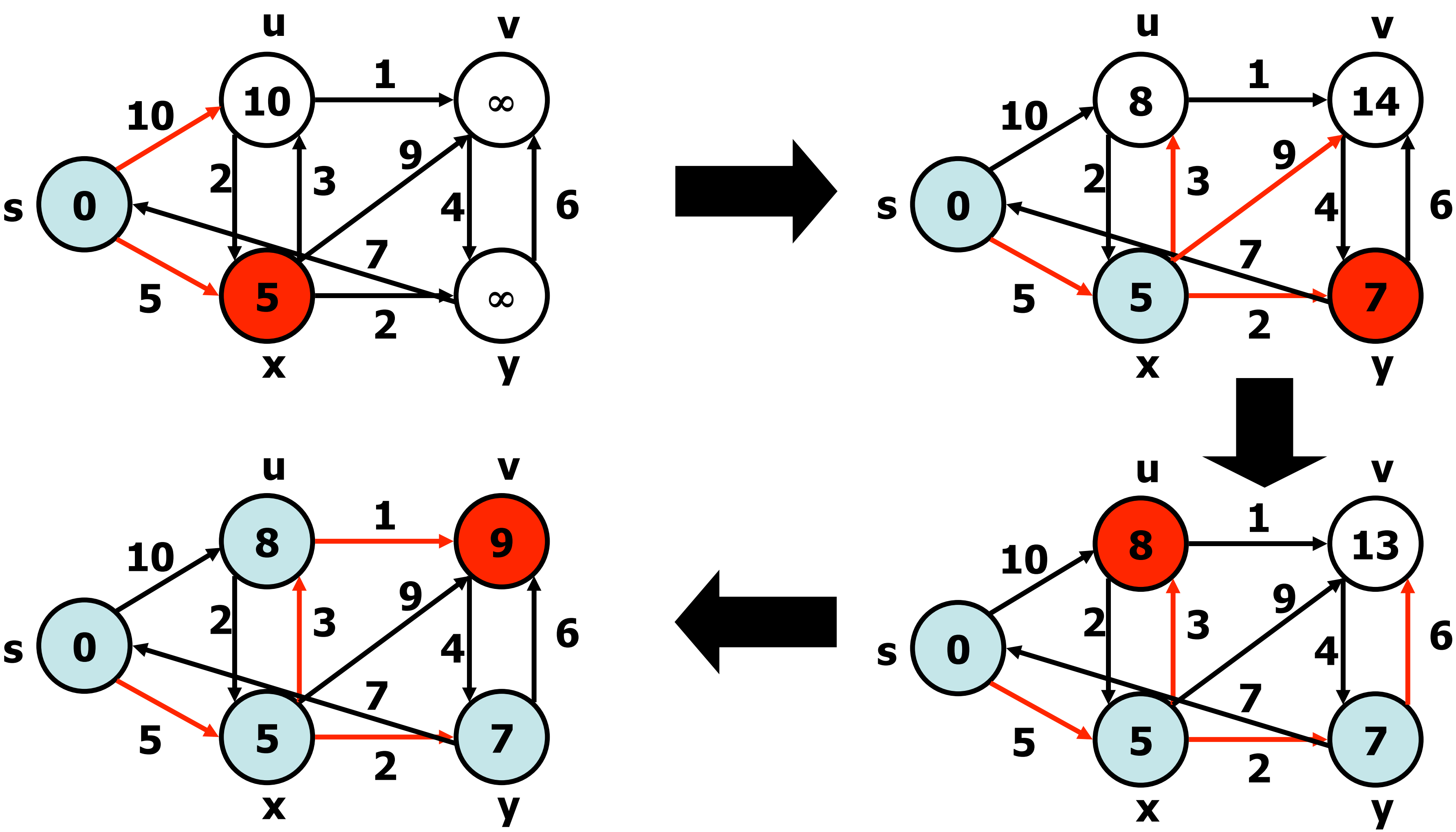
extract-min(Q): return vertex v in Q with minimal shortest-path estimate d[v]

Dijkstra's Algorithm: Example

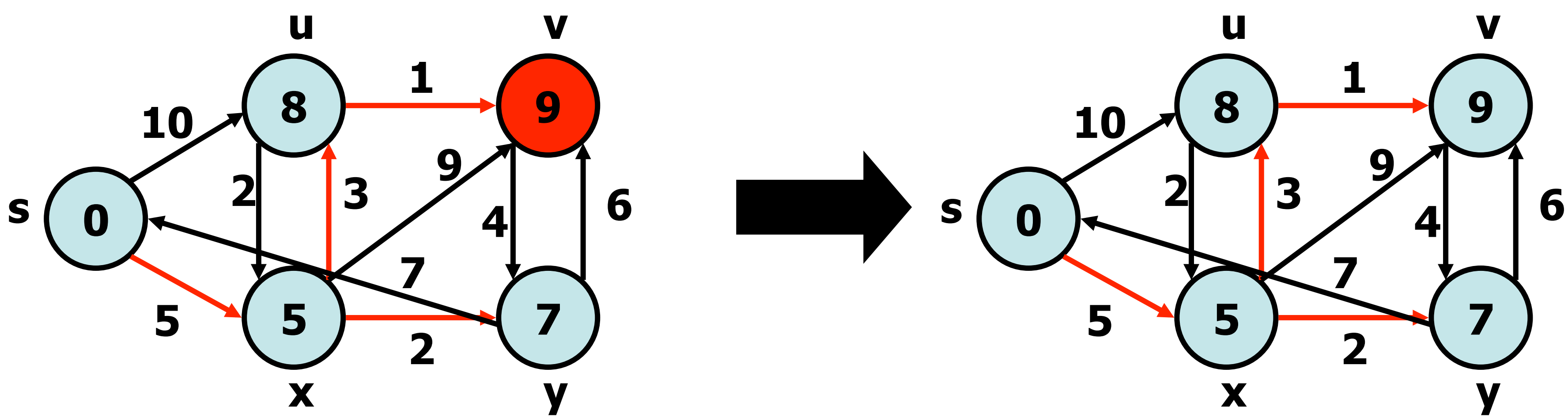


- s: source
- d[i]: number inside of vertex i
- π[b]: if (a, b) red, then π[b] = a
- members of set S: blue-shaded vertices
- members of priority queue Q: non-shaded vertices

Dijkstra’s Algorithm Example (cont’d)



Dijkstra's Algorithm Example (cont'd)



- At termination, know shortest-path routes from s to all other routers
- Shortest-path tree, rooted at s

Dijkstra’s Algorithm: Efficiency

- Most networks are sparse graphs
  - far fewer edges than $O(N^2)$
- Implement Q with binary heap
  - for N items in heap, cost of extract-min() is $O(\log_2 N)$
- Begin with |V| entries in Q, call extract-min() once for each
  - Cost: $O(V\log_2 V)$
- Total cost to insert |V| entries into Q: O(V)
- Each call to relax() reduces d[] value for vertex in Q
  - Cost: $O(\log_2 V)$
- At most |E| calls to relax()
- Total cost: $O((V + E) \log_2 V)$, or $O(E \log_2 V)$ when all vertices reachable from source

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Link State Routing: Properties

- At first glance, flooding status of all links seems costly
  - It is! Doesn't scale to thousands of nodes without other tricks, namely hierarchy (more when we discuss BGP)
  - Cost reasonable for networks of hundreds of routers
- In practice, for intra-domain routing, LS has won, and DV no longer used
  - LS: after flooding, no loops in routes, provided all nodes have consistent link state databases
  - LS: flooding offers fast convergence after topology changes
- LS more complex to implement than DV
  - Sequence numbers crucial to protect against stale announcements
  - Bringing up adjacencies
  - Maintains both link state database and routing table