CS 330: Network Applications & Protocols

Network Layer

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Overview of Network Layer

- **Virtual Circuit and Datagram Networks**
- **Router Architectures**
- **IP: Internet Protocol**
- **Routing algorithms**
  - Overview
  - Link state
  - Distance vector
- **Routing in the Internet**
- **Broadcast and multicast routing**

Network-layer functions

Recall: two network-layer functions:

- ***forwarding:*** move packets from router's input to appropriate router output

data plane

- ***routing***: determine route taken by packets from source to destination

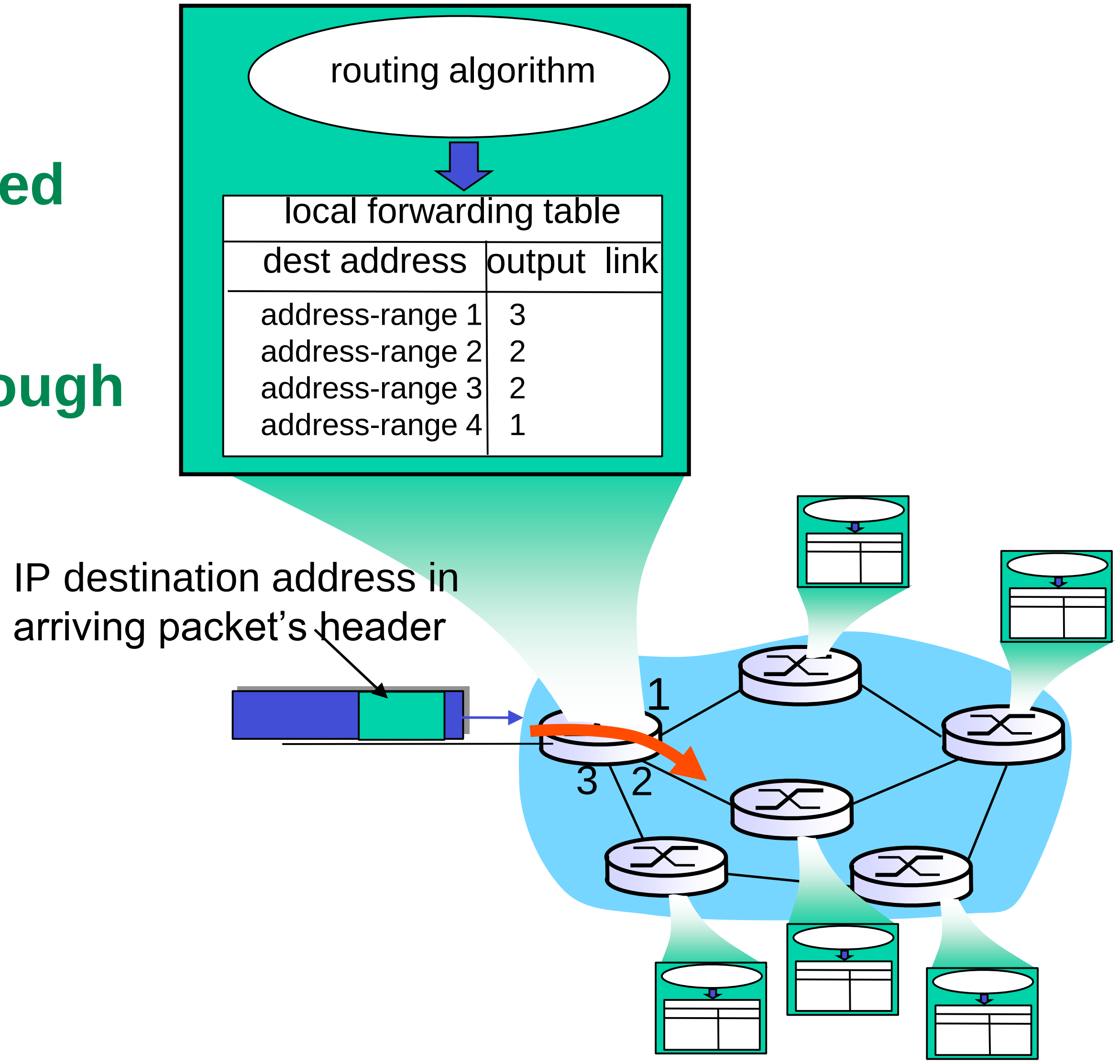
control plane

Two approaches to structuring network control plane:

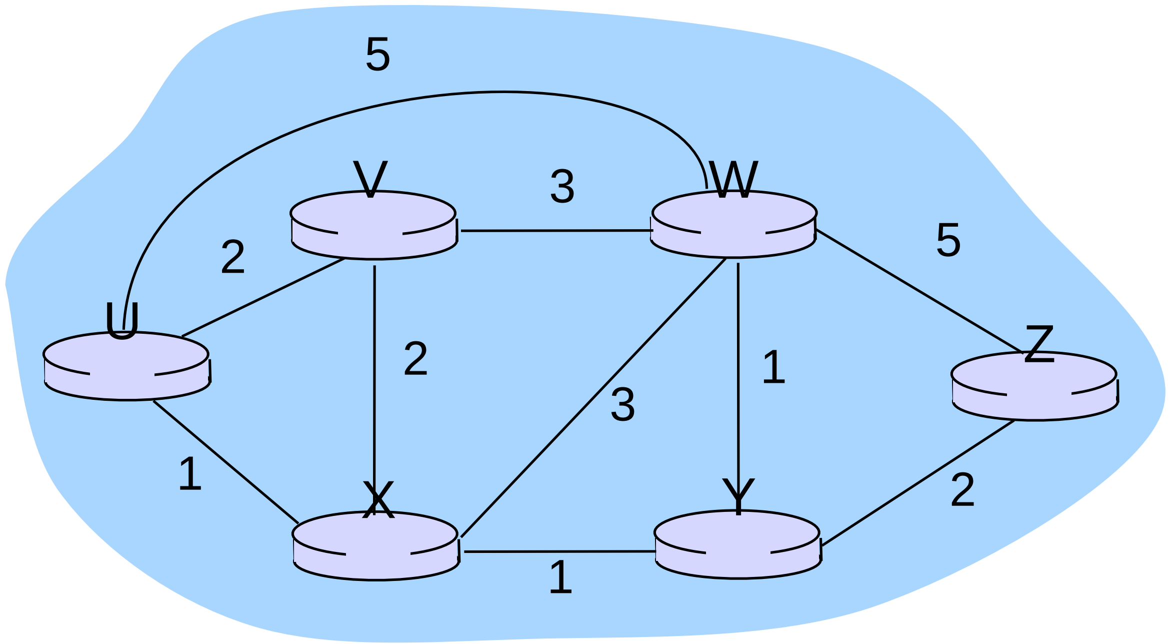
- per-router control (traditional)
- logically centralized control (software defined networking)

Overview

- **Routers use routing algorithms to maintain forwarding tables**
- **Routers exchange information with other routers to compute information that is entered into forwarding table**
- **Routing algorithms determine best path through a network from some source to some destination**
  - Least-cost path is best path
    - Cost of path can depend on: distance, congestion, $$ cost, or other factors
  - Networks are represented as graphs
    - Routers are nodes in the graph
    - Links between routers are edges in graph



Graph abstraction of the network



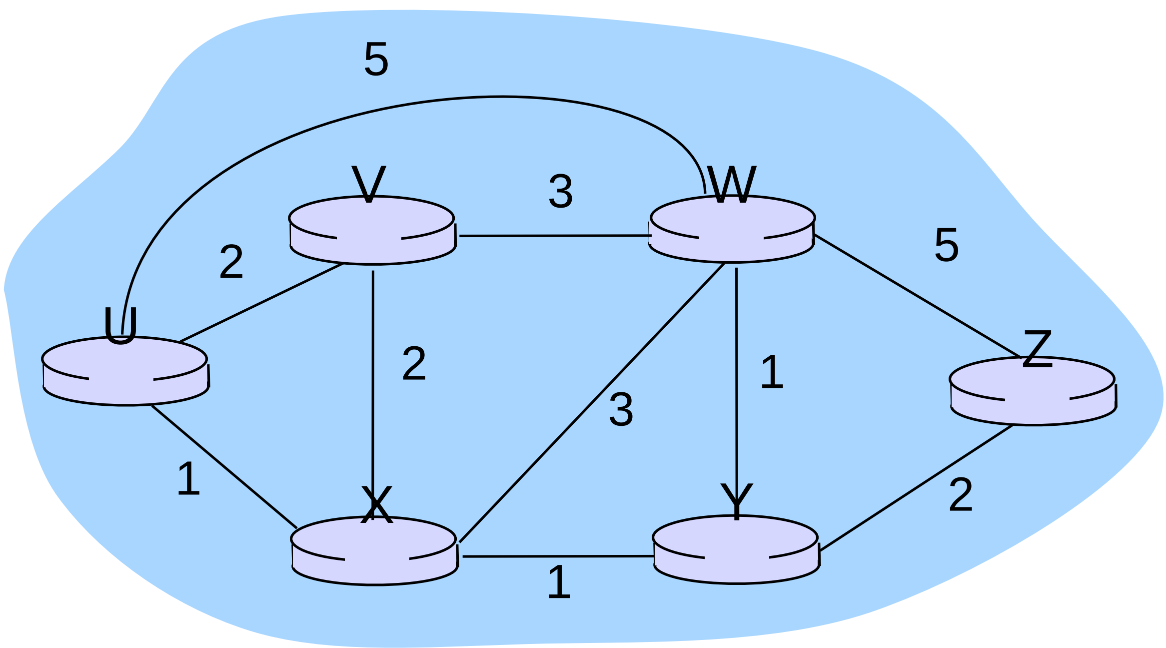
graph: G = (N,E)

N = set of routers = { u, v, w, x, y, z }

E = set of links ={ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }

aside: graph abstraction is useful in other network contexts, e.g., P2P, where *N* is set of peers and *E* is set of TCP connections

Graph abstraction: costs



$c(x,x')$ = cost of link (x,x')
e.g., $c(w,z) = 5$

cost could always be 1, or inversely related to bandwidth, or inversely related to congestion

cost of path $(x_1, x_2, x_3,\ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

key question: what is the least-cost path between u and z ?
routing algorithm: algorithm that finds that least cost path

Types of Routing Algorithms

- **Global Routing Algorithm**
  - All routers know complete network topology, and link cost info
  - Often called Link-state algorithms since the algorithm must know the state (i.e. cost) of all links in the network

- **Decentralized Routing Algorithm**
  - No router has complete information about the network or links costs
  - Routers know information about physically-connected neighbors, such as link costs to neighbors
    - Neighbors also exchange information about each others' neighbors
  - Calculation of least-cost path is determined iteratively in a distributed fashion
  - An example is the Distance-vector algorithm

Types of Routing Algorithms

- **Static Routing Algorithm**
  - Routes change slowly over time
  - Static routes are often entered by a human into a forwarding table

- **Dynamic Routing Algorithm**
  - Routes are not dependent on human input
  - Routes are periodically recomputed based on changes in the network
    - A new router is added
    - A router crashes
    - Too much congestion in part of the network
    - etc.
  - Must be intelligent to avoid creating routing loops in network

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Link-State Routing Algorithm

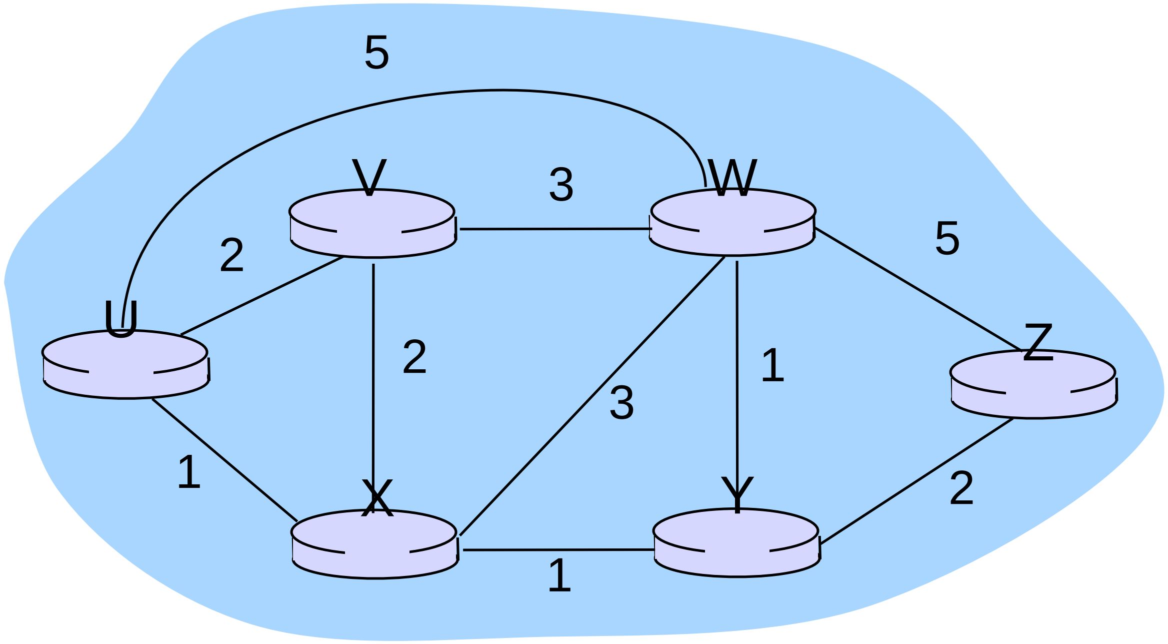
- **All routers know complete network topology, and link cost info**
  - Periodically, routers broadcast link-state information about each of their links to all other routers on the network
  - Network topology and link costs known to all routers
    - All nodes have same information about the network
  - Each router computes least-cost path from itself (the source) to *ALL* other routers on the network (the destinations)
    - Typically done using Dijkstra's algorithm
    - Result provides forwarding table for that node

Dijkstra's Algorithm

- **Algorithm works as follows:**
  - Starts by assigning some initial distance value for each node in the graph
    - Distance from node s to itself is 0
    - Distances from node s to all other nodes in graph are initialized to INFINITY
  - Operates in steps, where at each step the algorithm improves the distance values for nodes in the graph
  - At each step the shortest distance from node s to another node in the graph is determined

Dijkstra's Algorithm Example

- **Network is represented as a graph**
  - Routers are nodes in graph
  - Links are edges in graph
    - Cost of edge is labeled
- **Each router computes distance to all other routers in network**
  - Example shows computation done by router U



A link-state routing algorithm

Dijkstra's algorithm

- **net topology, link costs known to all nodes**
  - accomplished via "link state broadcast"
  - all nodes have same info
- **computes least cost paths from one node ('source") to all other nodes**
  - gives *forwarding table* for that node
- **iterative: after k iterations, know least cost path to k dest.'s**

notation:

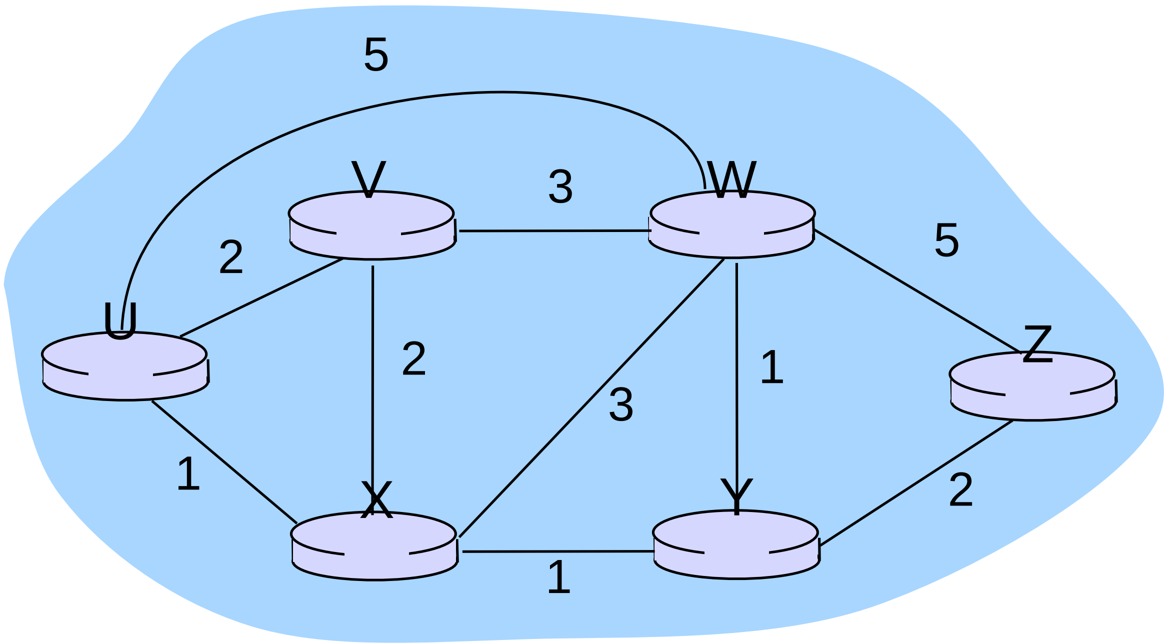
- **c(x,y): link cost from node x to y; = ∞ if not direct neighbors**
- **D(v): current value of cost of path from source to dest. v**
- **p(v): predecessor node along path from source to v**
- **N': set of nodes whose least cost path definitively known**

Dijsktra's algorithm

```
Initialization:
  N' = {u}
  for all nodes v
    if v adjacent to u
        then D(v) = c(u,v)
    else D(v) = ∞

 Loop
   find w not in N' such that D(w) is a minimum
    add w to N'
    update D(v) for all v adjacent to w and not in N' :
       D(v) = min( D(v), D(w) + c(w,v) )
    /* new cost to v is either old cost to v or known
     shortest path cost to w plus cost from w to v */
  until all nodes in N'
```

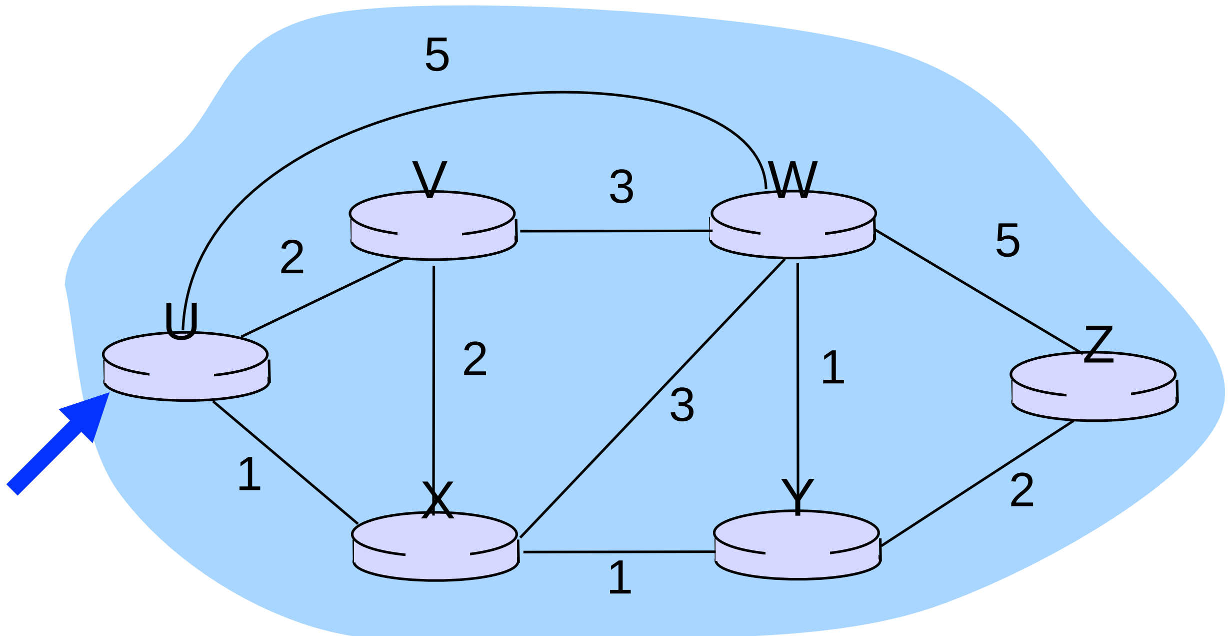
Dijkstra's Algorithm Example (Node U)



Initialize distances to U:
- Distance to itself is 0
- Distance to all other nodes is ∞

Node	Distance Computation from U						Path
U							
V							
W							
X							
Y							
Z							

Dijkstra's Algorithm Example (Node U)

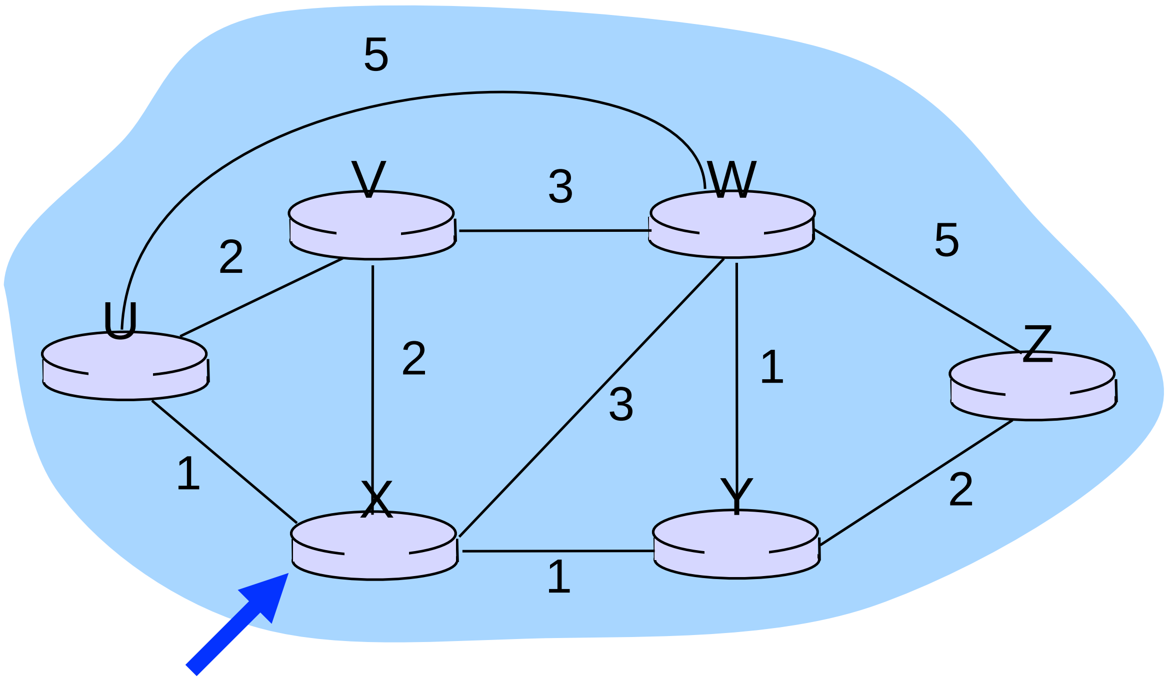


Select node with shortest distance to U (currently U) and determine shortest distance of its neighbors from U

- If node is unreachable it is still ∞
- Record the path

Node	Distance Computation from U						Path
U							
V							
W							
X							
Y							
Z							

Dijkstra's Algorithm Example (Node U)

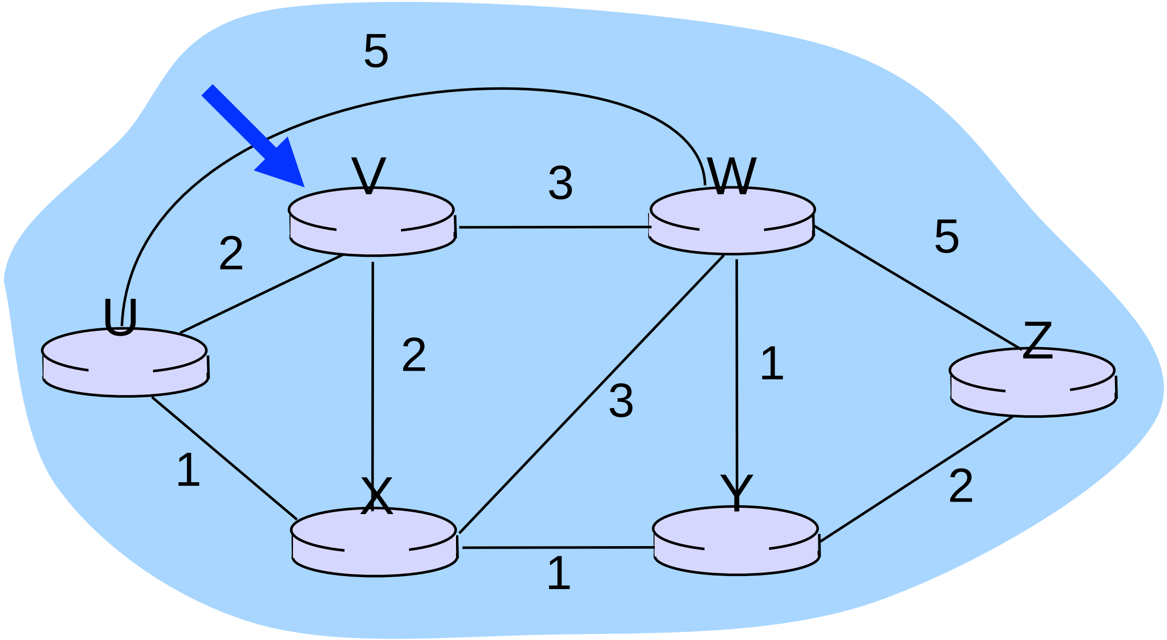


Select node with shortest distance to U (currently X) and determine shortest distance of its neighbors from U

- Node selected is min distance

Node	Distance Computation from U						Path
U							
V							
W							
X							
Y							
Z							

Dijkstra’s Algorithm Example (Node U)

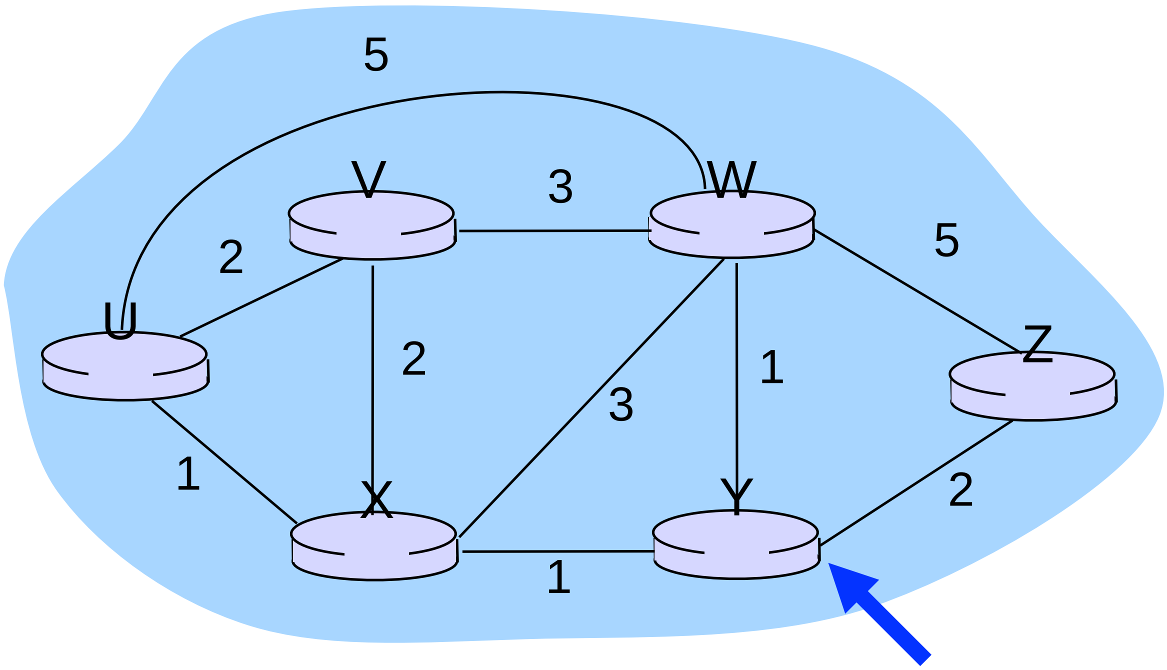


Select node with shortest distance to U (currently X) and determine shortest distance of its neighbors from U

- Node selected is min distance

Node	Distance Computation from U						Path
U							
V							
W							
X							
Y							
Z							

Dijkstra's Algorithm Example (Node U)

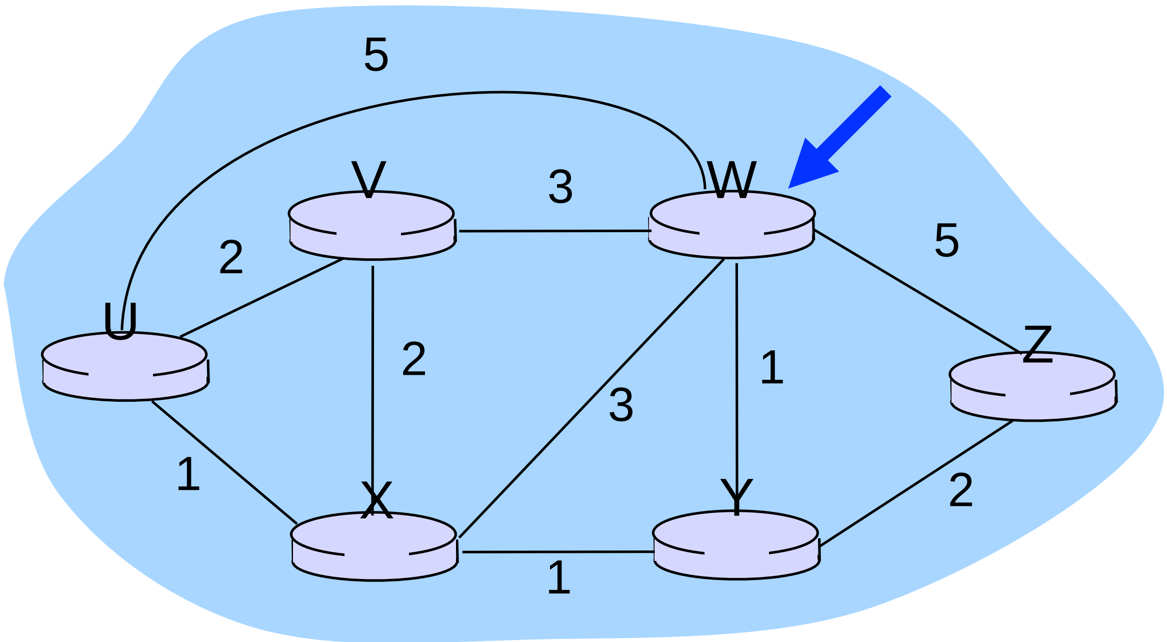


Select node with shortest distance to U (currently Y) and determine shortest distance of its neighbors from U

- Node selected is min distance

Node	Distance Computation from U						Path
U							
V							
W							
X							
Y							
Z							

Dijkstra’s Algorithm Example (Node U)

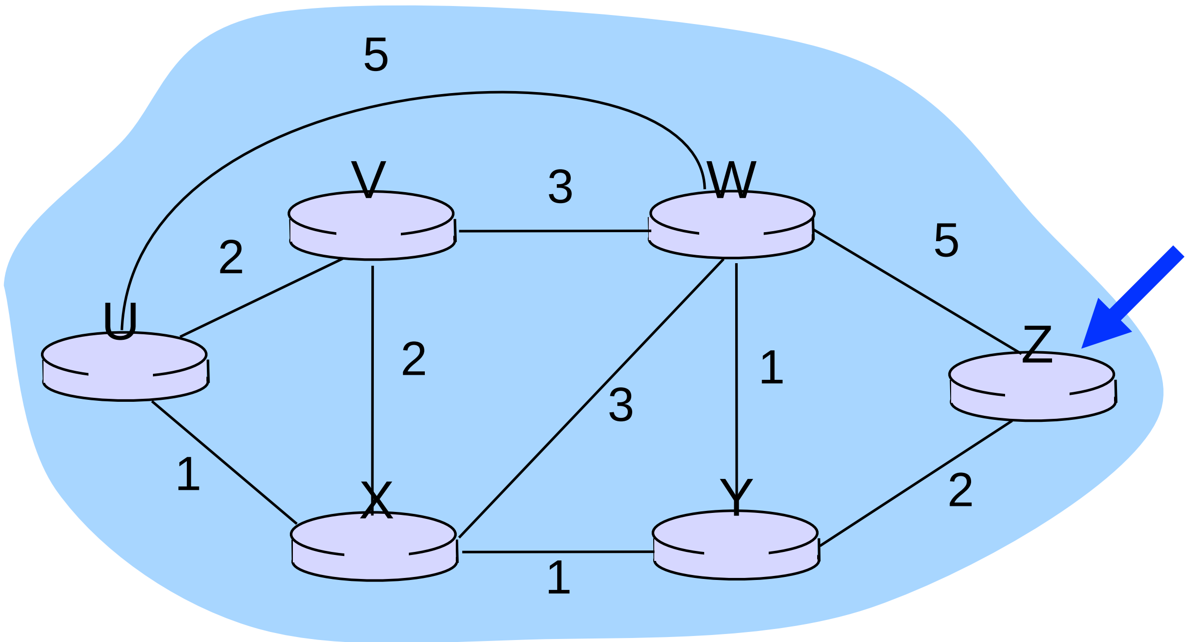


Select node with shortest distance to U (currently W) and determine shortest distance of its neighbors from U

- Node selected is min distance

Node	Distance Computation from U						Path
U							
V							
W							
X							
Y							
Z							

Dijkstra's Algorithm Example (Node U)



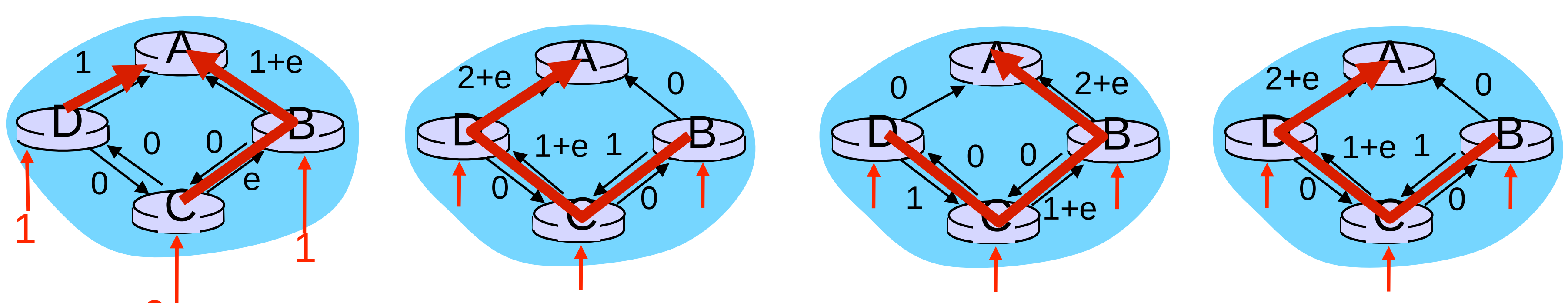
Select node with shortest distance to U (currently Z) and determine shortest distance of its neighbors from U

- All nodes have been accounted for, so terminate

Node	Distance Computation from U						Path
U							
V							
W							
X							
Y							
Z							

Dijkstra’s Algorithm Considerations

- **When using Dijkstra’s algorithm dynamically, oscillations are possible**
  - For example, if link cost equals amount of carried traffic
    - Links with no traffic have low cost ..
    - So all traffic is rerouted down those links
    - Then a different set of links will have lower cost



e
Initially

Given these costs, find new routing…. resulting in new costs

Given these costs, find new routing…. resulting in new costs

Given these costs, find new routing…. resulting in new costs

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Distance Vector Algorithm

- **No router has complete information about the network or links costs**
- **Routers know information about physically-connected neighbors, such as link costs to neighbors**
- **Key idea**
  - From time-to-time, each node sends its own distance vector estimate to its neighbors
  - When x receives new DV estimate from neighbor, it updates its own DV using the Bellman-Ford algorithm

Let
$d_x(y)$:= cost of least-cost path from x to y
then
$d_x(y) = min_v\{ c(x,v) + d_v(y) \}$

Cost from neighbor v to destination y
Cost to neighbor v
min taken over all neighbors v of x

Distance Vector Algorithm

- **Algorithm is:**
  - Iterative and asynchronous
    - Each local iteration caused by:
      - Local link cost change
      - DV update message from neighbor
  - Distributed
    - Each node notifies neighbors only when its DV changes
      - Neighbors then notify their neighbors if necessary

At Each Node:

Wait for change in local link cost or msg from neighbor

↓

Recompute estimates

↓

If DV to any dest has changed, *notify* neighbors

Distance Vector Example

Node x table

from \ cost to	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

Node y table

from \ cost to	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

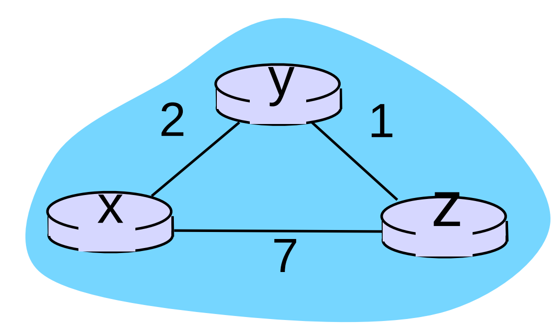
Node z table

from \ cost to	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	3	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

time



Distance Vector Considerations

- **When link costs change**
  - Good news travels quickly
    - When link cost decreases, notifying neighbors is quick
  - Bad news travels slowly
    - When link cost increases, can cause routing loops that last for long periods of time (see text section 5.5.2)

Comparison of LS and DV algorithms

message complexity

- ***LS:*** **with n nodes, E links, O(nE) msgs sent**
- ***DV:*** **exchange between neighbors only**
  - convergence time varies

speed of convergence

- ***LS:*** **$O(n^2)$ algorithm requires O(nE) msgs**
  - may have oscillations
- ***DV:*** **convergence time varies**
  - may be routing loops
  - count-to-infinity problem

robustness: **what happens if router malfunctions?**

LS:

- node can advertise incorrect *link* cost
- each node computes only its *own* table

DV:

- DV node can advertise incorrect *path* cost
- each node's table used by others
  - error propagate thru network

Hierarchical Routing

- **Routing protocols within a single network (an autonomous system) are determined by some network administrator**
  - Provide routing information for hosts *within the network* (i.e. Intra-AS routing)
  - For example, a company or ISP would use some routing protocol for their network
- **Routers within an AS also need a way to route packets to hosts on other networks**
  - Route packets to gateway router that will direct packets to the next network (AS)
    - All packets destined for another network are routed to the gateway router
  - What if there are multiple gateways? To which gateway should packets get routed?
    - Handled by inter-AS routing protocols (BGP)
    - Routers get information from both intra and inter-AS routing protocols and maintain info in forwarding table