COSC264

Introduction to Computer Networks and the Internet

Introduction to Routing- Link State Routing

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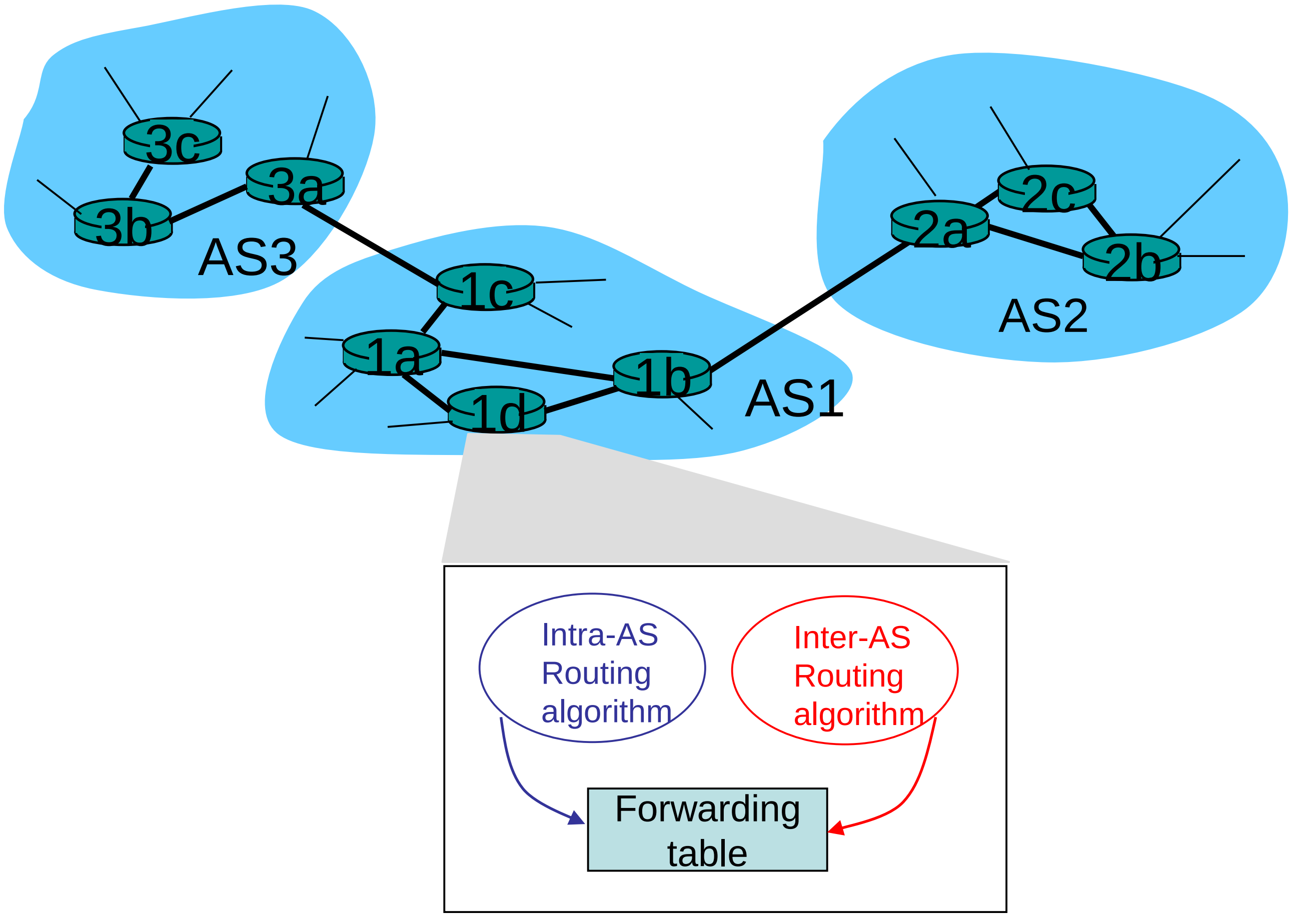
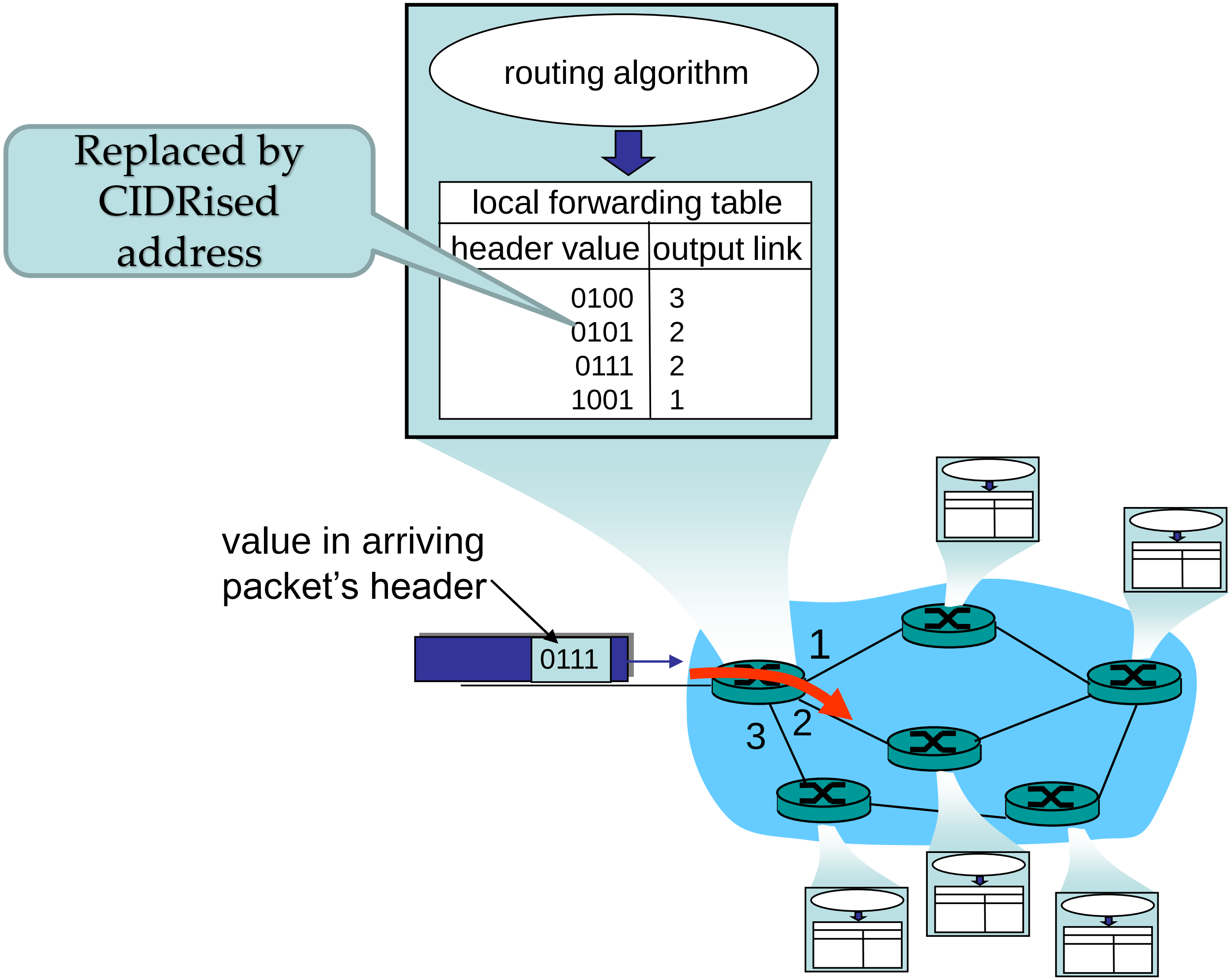
A quick review

- Layer approach and services
- Hierarchical routing and Autonomous System (AS)
- Routing vs forwarding
- Classification of routing algorithms

Hierarchical routing in the Internet



Routing and Forwarding



Outline – today

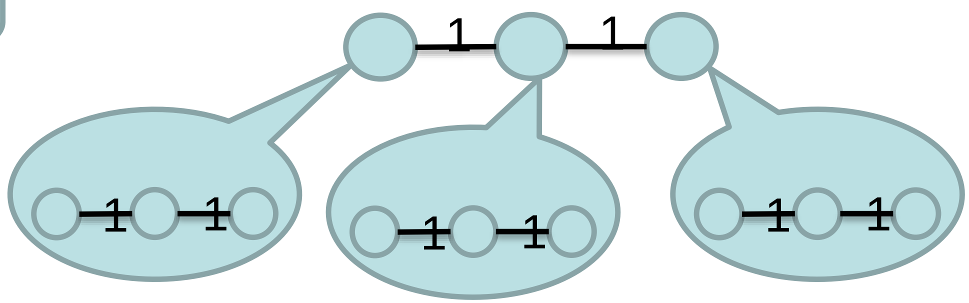
- Network layer overview
- Routing overview
- Link-state routing (Dijkstra’s algorithm)
- Distance-vector routing (Bellman-Ford)
- Summary

Routing Algorithms and Routing Protocols

Intra-AS Routing

Routing Protocols	Routing Algorithms
RIP	Bellman-Ford (Distance-vector) Algorithm
OSFP	Dijkstra's Algorithm
BGP	Bellman-Ford (Distance-vector) Algorithm

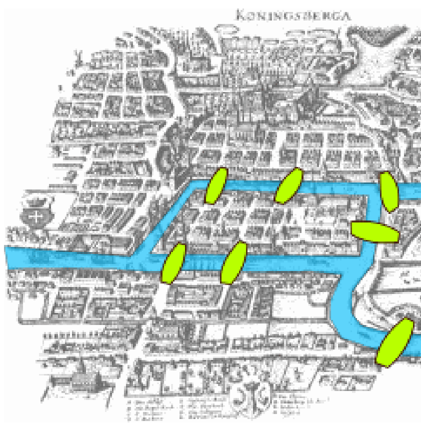
Inter-AS Routing

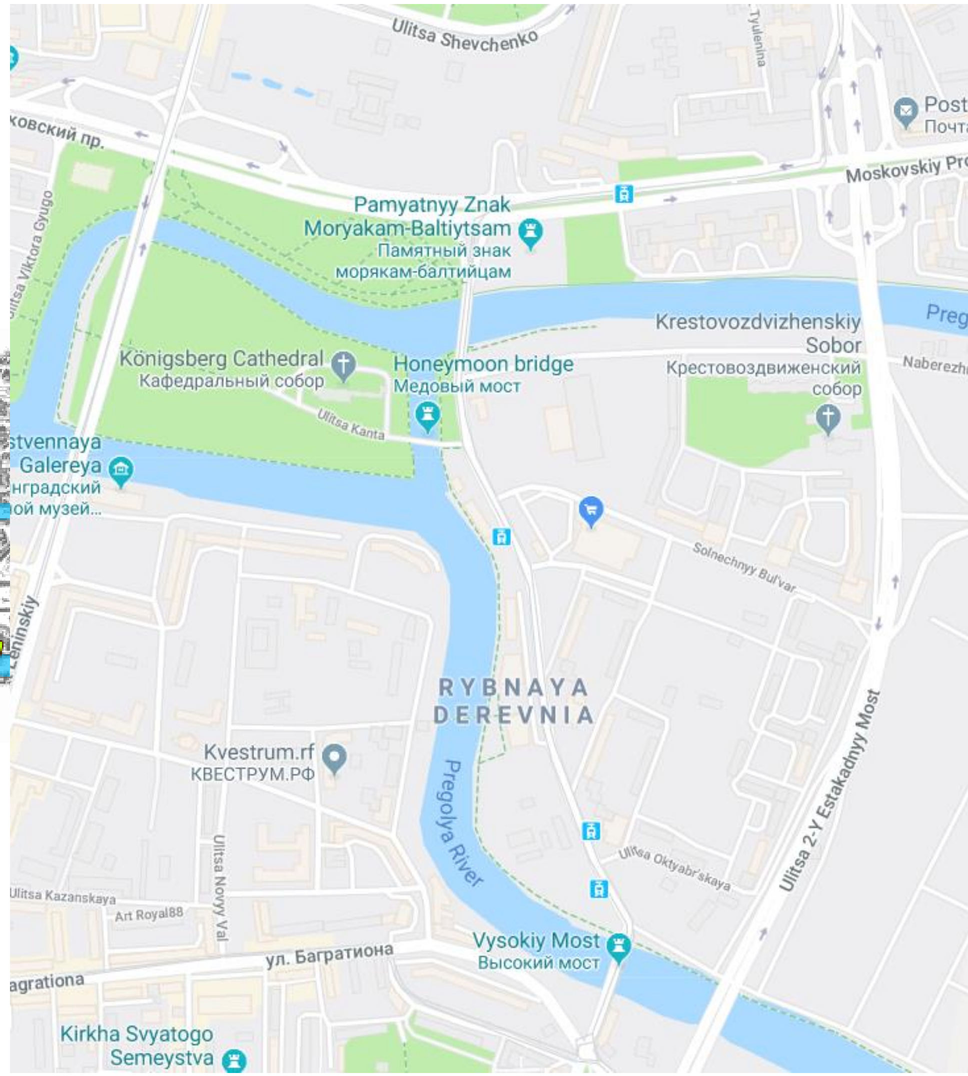


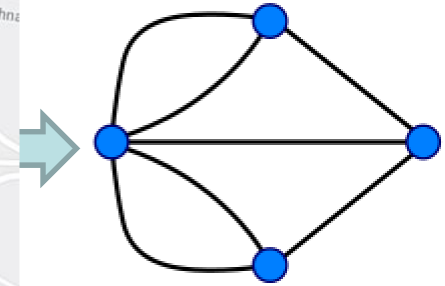
The Internet routing protocols (RIP, OSPF, and BGP) are ***load-insensitive***.

Euler and Graph Theory

- Seven Bridges of Königsberg. 1783
- Wiki

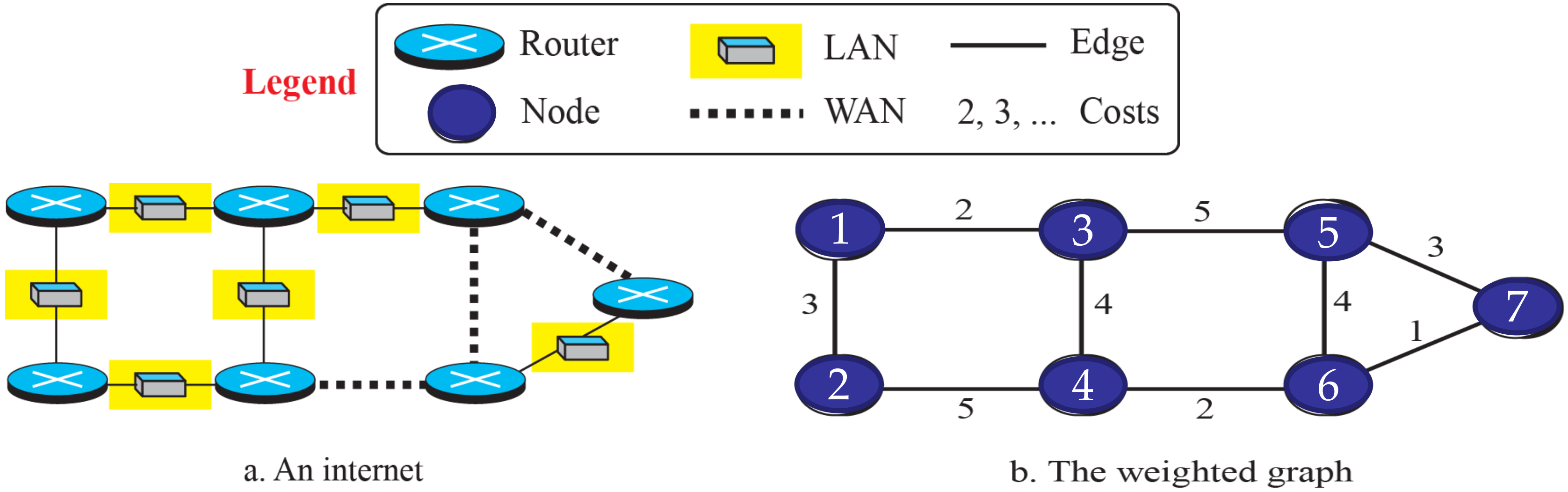






Modeling a network

- A network and its graphical representation



A graph G as an ordered pair $G = (V, E)$ where

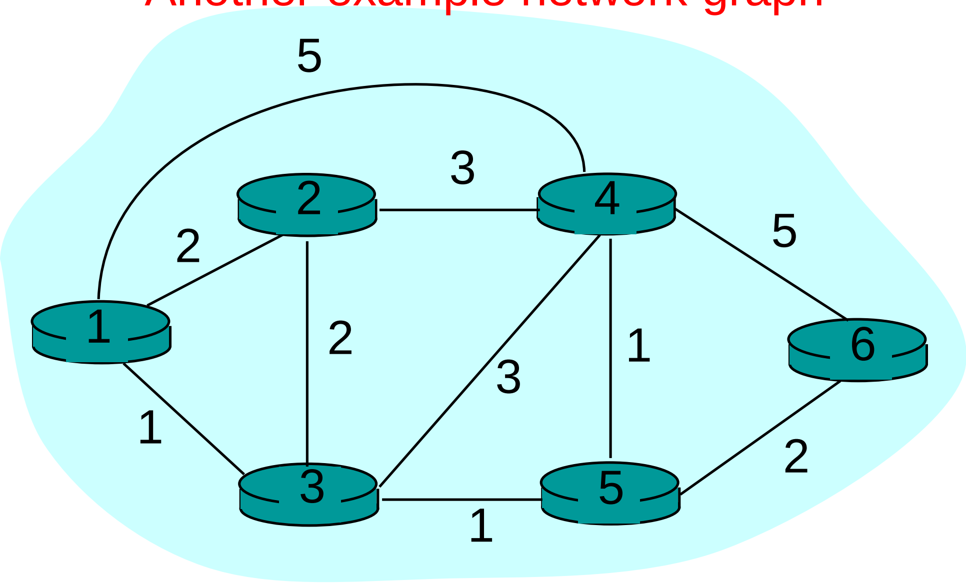
- V is a set of nodes (vertices) for routers; nodes are vertices $v_i \in V$
  - e.g., $V=\{1,2,3,\ldots,N\}$
- E is a set of edges (links); $e_{ij} = (v_i, v_j) \in E$
  - $E \subset V \times V$; $E = \{(1,2), (1,3), (2,4), (3,4), (3,5), (4,6), (5,6), (5,7), (6,7)\}$
  - v_i and v_j are neighbors
  - Edge weights are costs

Figure 20.1 from Forouzan's book (5th ed.)

Modeling a network (2)

- Modeled as a graph
  - Routers $\Rightarrow$ nodes
  - Link $\Rightarrow$ edges

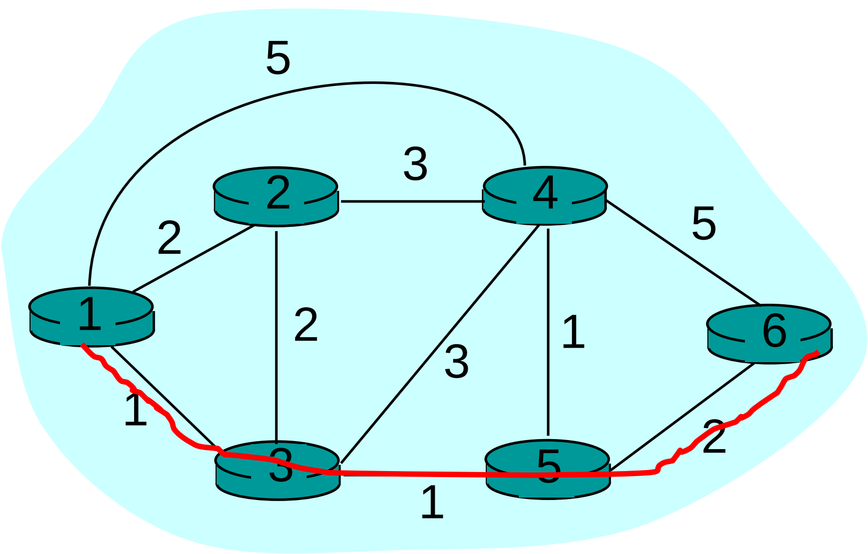
Another example network graph

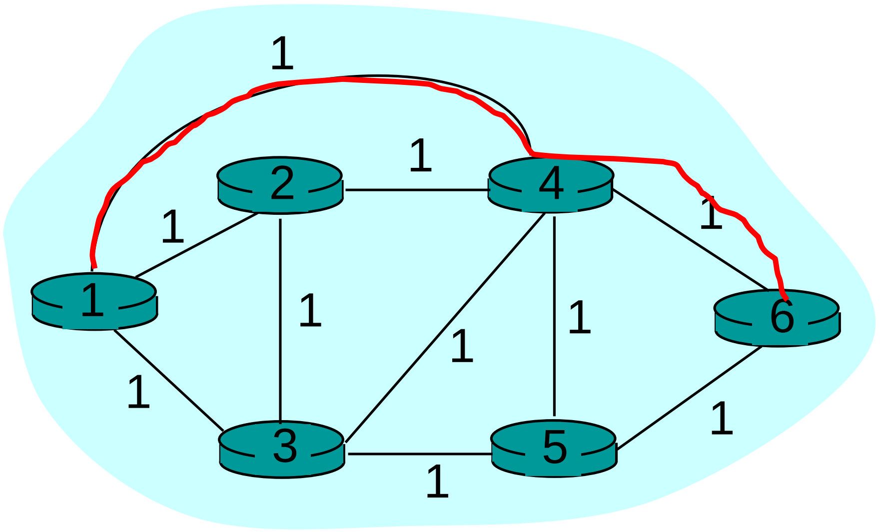


- Edge labels (called metrics) can be interpreted differently
  - as costs, e.g., delay, monetary transmission costs, geographical distance
  - as available resources, e.g., number of available phone trunks, current available capacity given the set of flows that already use this link

Routing algorithms

- To find least cost path
  - **Shortest path** if all link costs equal (measures hops)

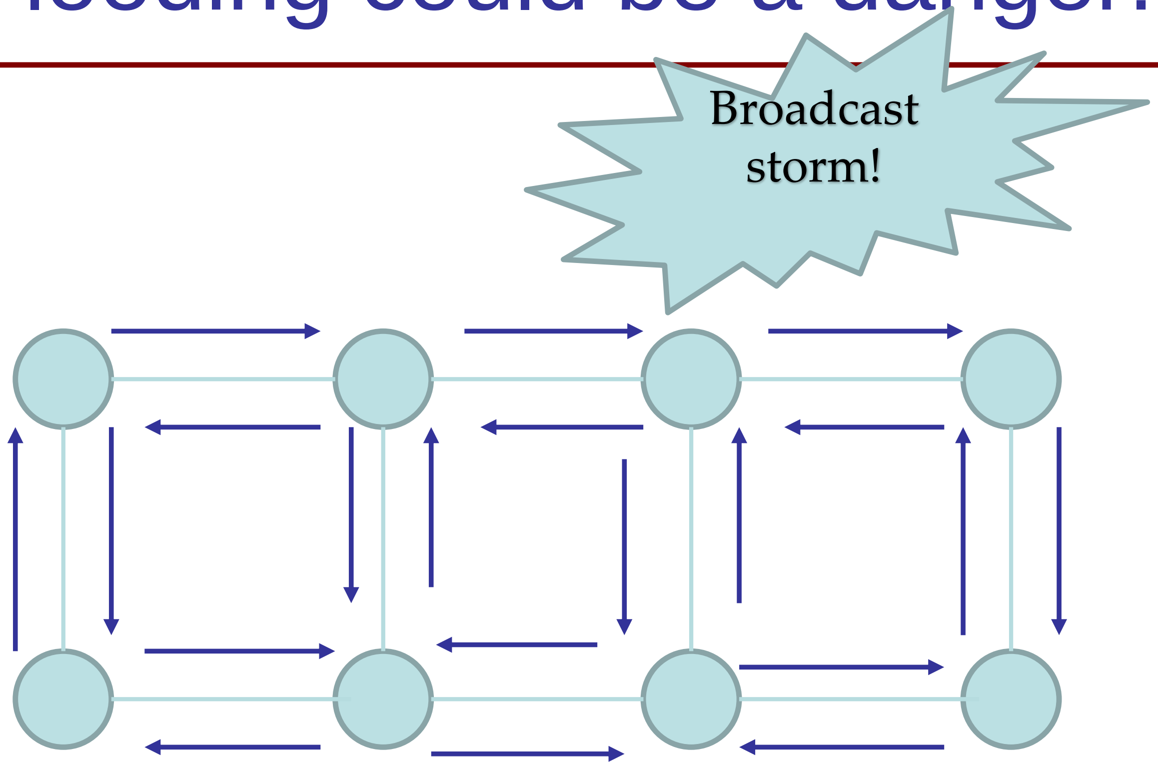




Link State Routing

- Each router has **complete network picture**
  - Topology, Link costs
- How does each router get the global state?
  - Each router reliably **floods** information about its neighbors to every other router; authentication;
  - All routers have consistent information;

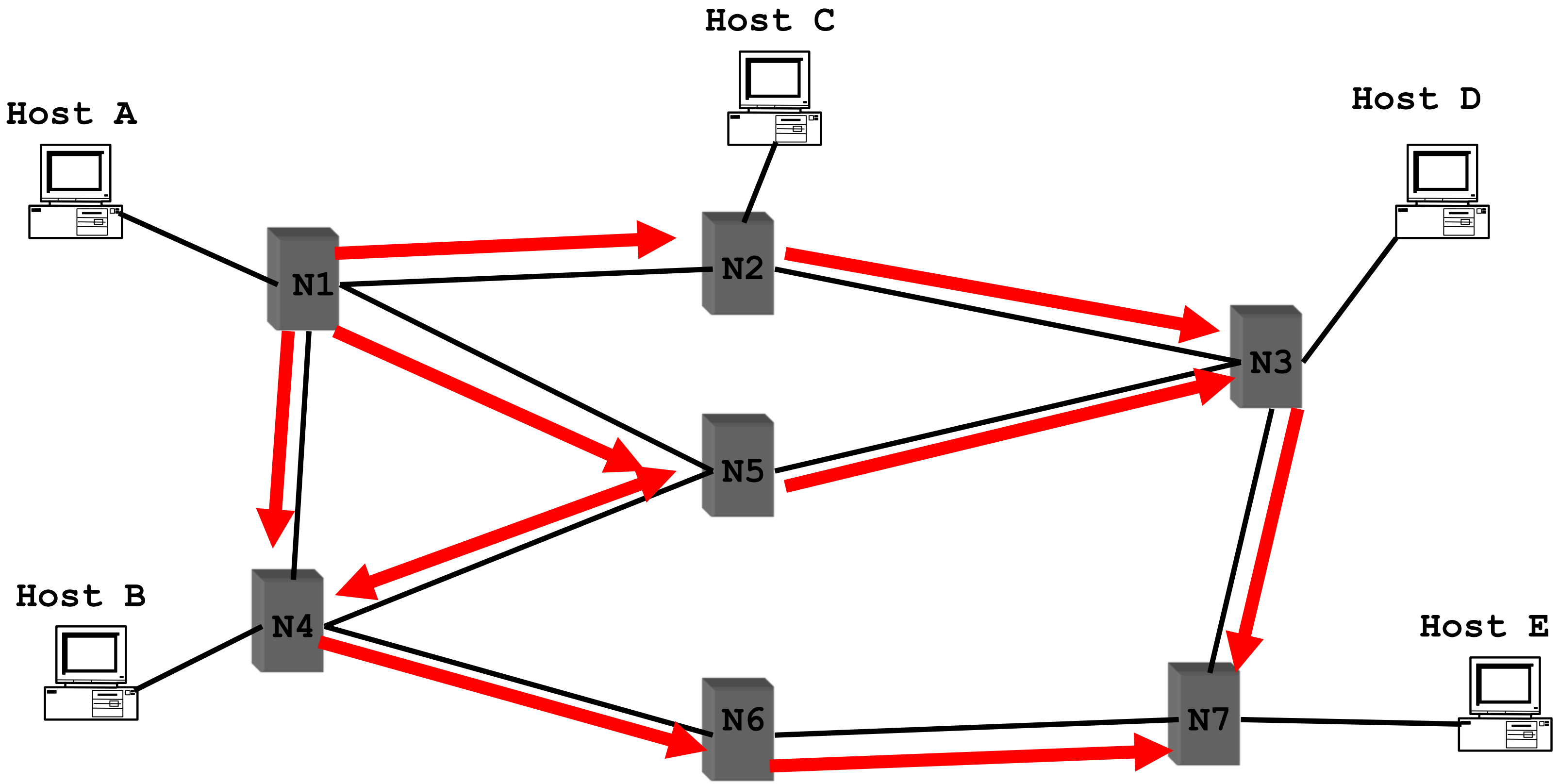
Flooding could be a danger!



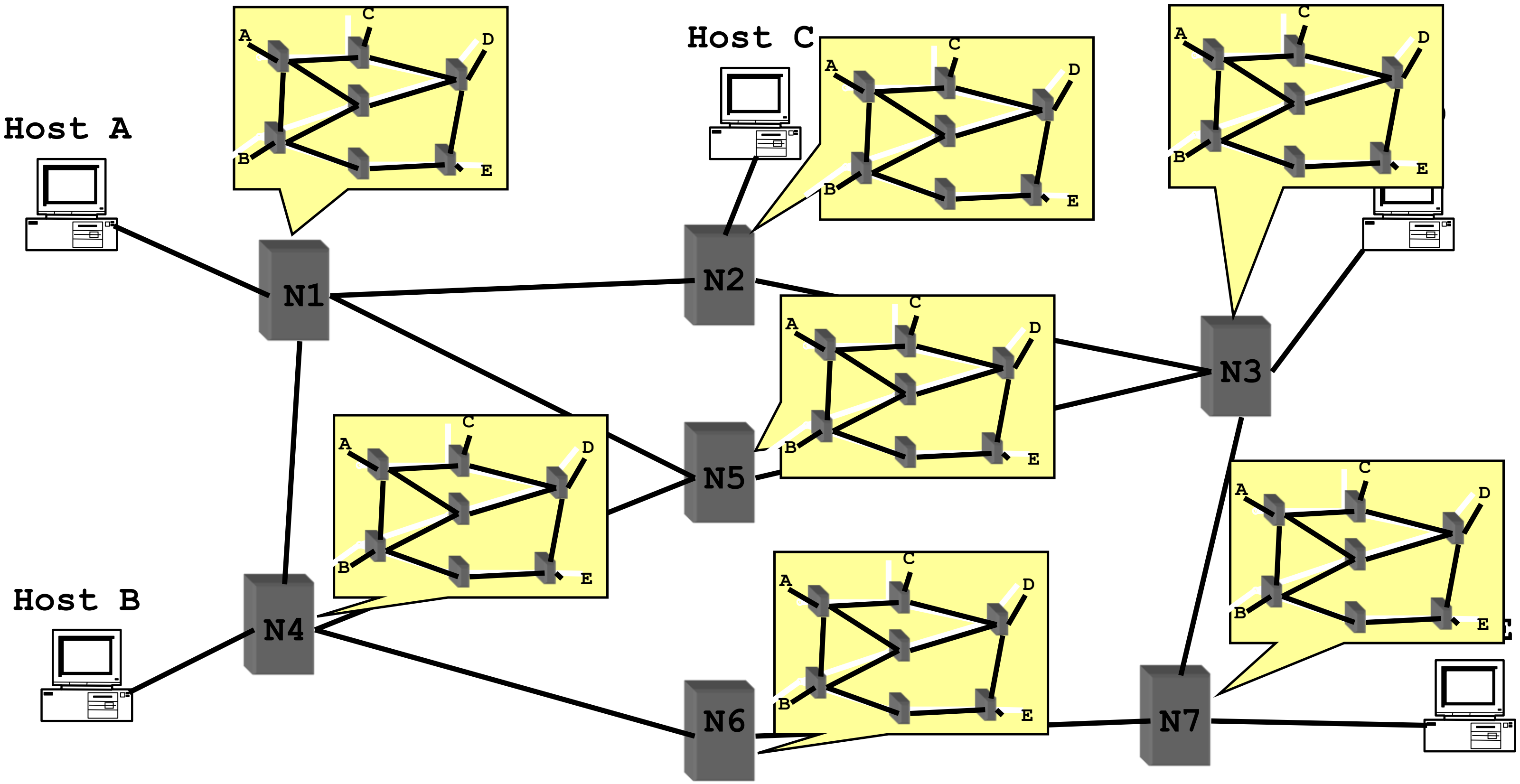
There are sophisticated algorithms doing the broadcasting job! (Controlled flooding, spanning-tree broadcast; refer to 4.7 of [KR3].)

Link State: Control Traffic

- Each node floods its local information
- Each node ends up knowing the *entire* network topology node

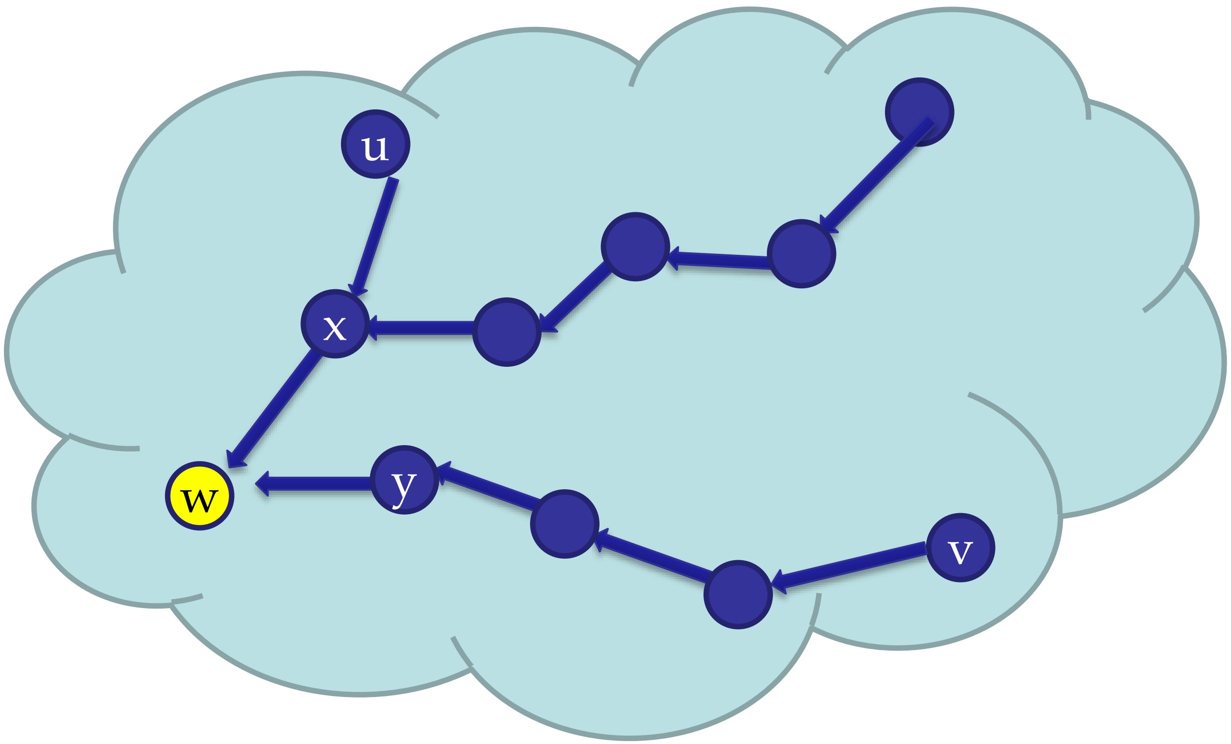


Link State: Node State



Link State Routing

- Each router independently calculates the least-cost path from itself to every other router
  - Using Dijkstra's Algorithm;
  - Generates a forwarding table for every destination;



Dest.	Next-hop
u	x
v	y
…	…

Dijkstra's Algorithm

- INPUT:
  - Network topology (graph), with link costs
- OUTPUT:
  - Least cost paths from one node to all other nodes

Dijkstra's Algorithm

- **S**: nodes whose least-cost path already known
  - Initially, **S = {*u*}** where *u* is the source node
  - Add one node to **S** in each iteration
- **D(v)**: current cost of path from source to node *v*
  - Initially, **D(v) = c(*u*,*v*)** for all nodes *v* adjacent to *u*
  - … and **D(v) = ∞** for all other nodes *v*
  - Continually update **D(v)** as shorter paths are learned
- *p(v):* predecessor node along path from source to *v*, that is next to *v*

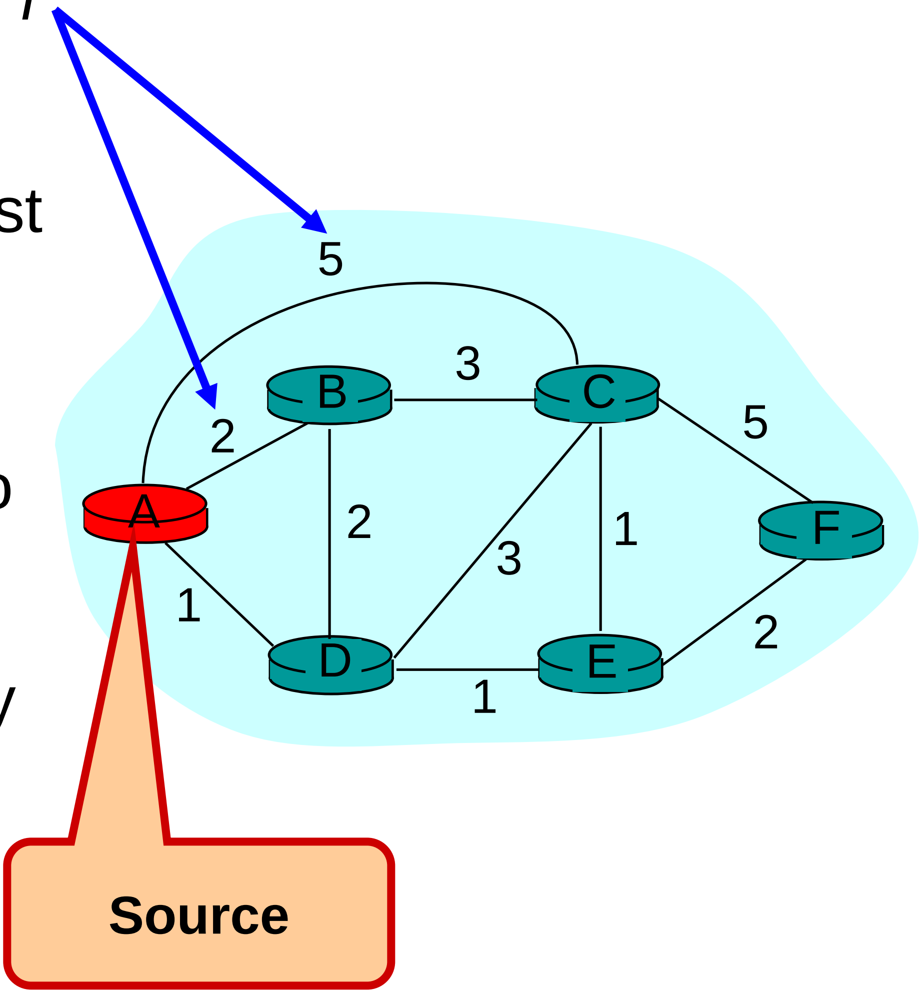
Dijkstra's Algorithm

```
Initialization:
  S = {u} /* u is the source*/
  for all nodes v
    if v is adjacent to u {
        then D(v) = c(u,v) /* cost of neighbor known*/
        else D(v) = ∞ /* cost of others unknown*/

Loop
  find w not in S with the smallest D(w)
  add w to S
  update D(v) for all v adjacent to w and not in S:
      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 S
```

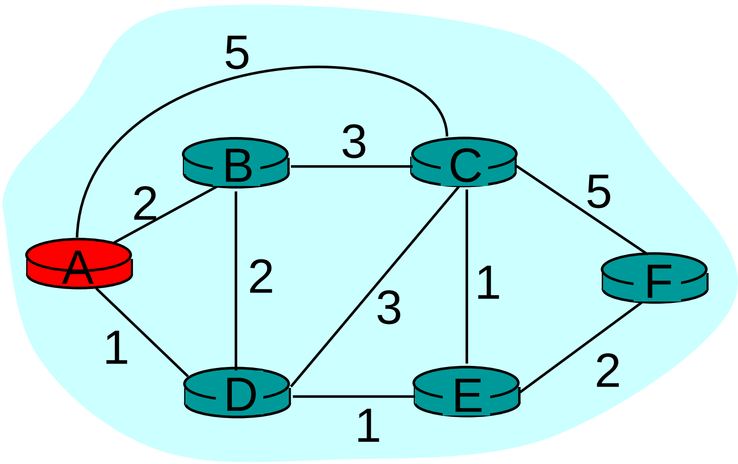
Dijsktra’s Algorithm with another example

- *c(i,j):* link cost from node *i* to *j*; cost infinite if not direct neighbors; **≥ 0**
- *D(v):* current value of cost of path from source to destination *v*
- *p(v):* predecessor node along path from source to *v*, that is next to *v*
- *S*: set of nodes whose least cost path definitively known



Example: Dijkstra's Algorithm

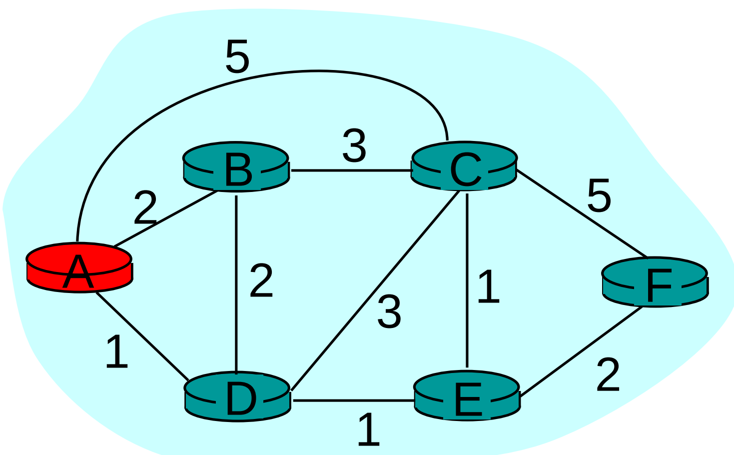
Step	start S	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1						
2						
3						
4						
5						



1 ***Initialization:***
2   **S** = {A};
3   for all nodes ***v***
4   if ***v*** is adjacent to ***A***
5   then D(v) = c(A,v);
6   else D(v) = ∞;
…

Example: Dijkstra's Algorithm

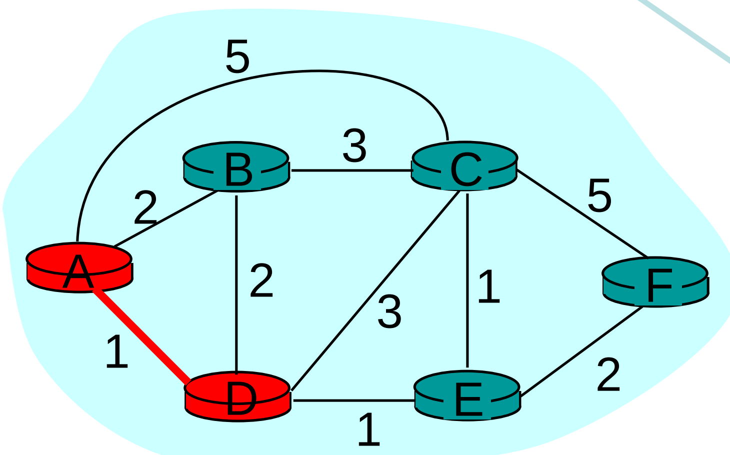
Step	start S	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1						
2						
3						
4						
5						




```
…
Loop
    find w not in S s.t. D(w) is a minimum;
    add w to S;
    update D(v) for all v adjacent
        to w and not in S:
    If D(w) + c(w,v) < D(v) then D(v) =
    D(w) + c(w,v); p(v) = w;
until all nodes in S;
```

Example: Dijkstra's Algorithm

Step	start S	D(B),p(B)	D(C),p(C)	**D(D),p(D)**	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1	AD					
2						
3						
4						
5						

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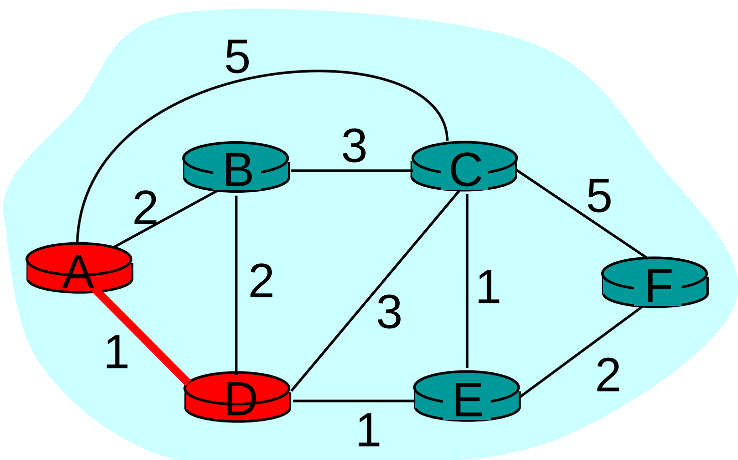
…
Loop
    find w not in S s.t. D(w) is a minimum;
    add w to S;
  update D(v) for all v adjacent
      to w and not in S:
  If D(w) + c(w,v) < D(v) then
    D(v) = D(w) + c(w,v); p(v) = w;
  until all nodes in S;
```

Example: Dijkstra's Algorithm

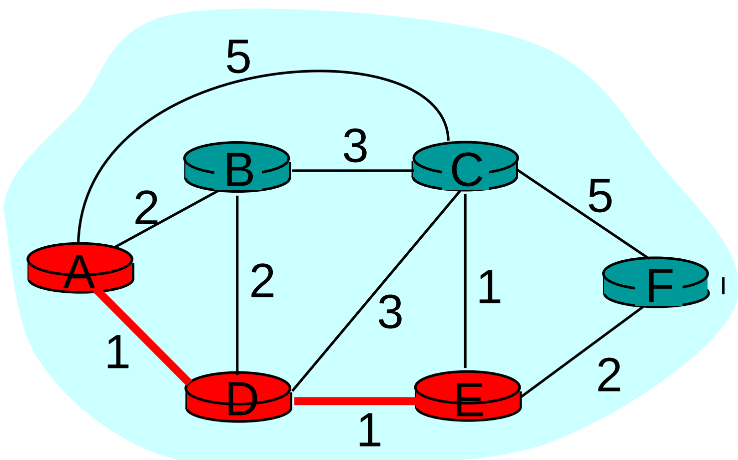
Step	start S	D(B),p(B)	D(C),p(C)	**D(D),p(D)**	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	**1,A**	∞	∞
1	AD		4,D		2,D	
2						
3						
4						
5						




```
…
Loop
    find w not in S s.t. D(w) is a minimum;
    add w to S;
   update D(v) for all v adjacent
      to w and not in S:
   If D(w) + c(w,v) < D(v) then
   D(v) = D(w) + c(w,v); p(v) = w;
    until all nodes in S;
```

Example: Dijkstra's Algorithm

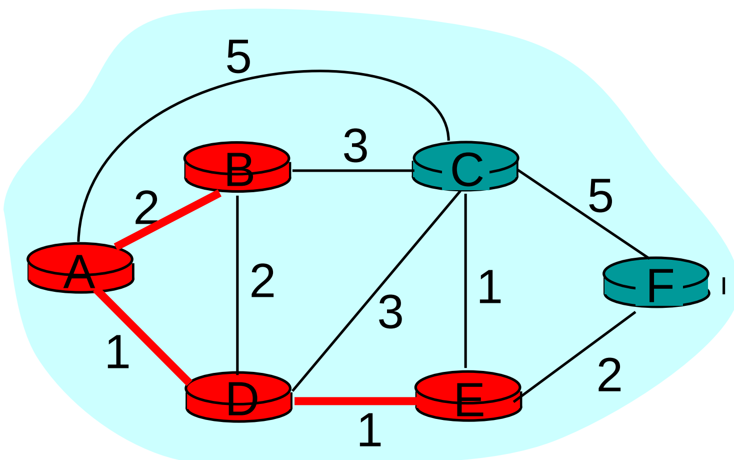
Step	start S	D(B),p(B)	D(C),p(C)	**D(D),p(D)**	**D(E),p(E)**	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1	AD		4,D		2,D	
2	ADE		3,E			4,E
3						
4						
5						



...
Loop
  find **w** not in **S** s.t. D(w) is a minimum;
  add **w** to **S**;
  update D(v) for all **v** adjacent
    to **w** and not in **S**:
  If D(w) + c(w,v) < D(v) then
    D(v) = D(w) + c(w,v); p(v) = w;
until all nodes in S;

Example: Dijkstra's Algorithm

Step	start S	**D(B),p(B)**	D(C),p(C)	**D(D),p(D)**	**D(E),p(E)**	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1	AD		4,D		2,D	
2	ADE		3,E			4,E
3	ADEB					
4						
5						



…

Loop

find **w** not in **S** s.t. D(w) is a minimum;

add **w** to **S**;

update D(v) for all **v** adjacent to **w** and not in **S**:

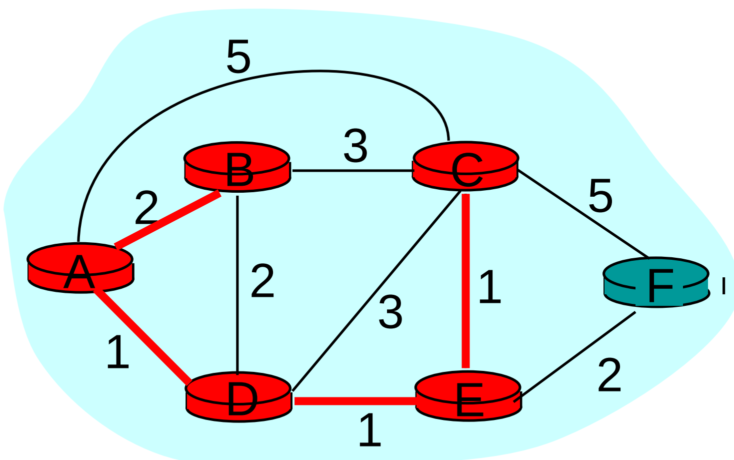
If D(w) + c(w,v) < D(v) then

D(v) = D(w) + c(w,v); p(v) = w;

until all nodes in S;

Example: Dijkstra's Algorithm

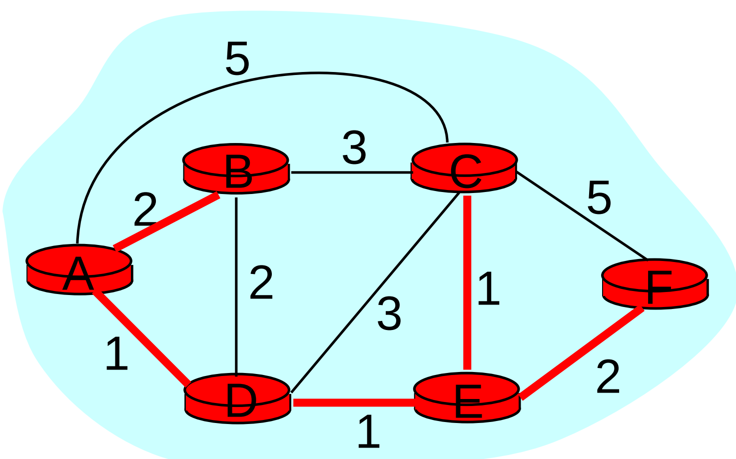
Step	start S	**D(B),p(B)**	**D(C),p(C)**	**D(D),p(D)**	**D(E),p(E)**	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1	AD		4,D		2,D	
2	ADE		3,E			4,E
3	ADEB					
4	ADEBC					
5						




```
…
8  Loop
9      find w not in S s.t. D(w) is a minimum;
10     add w to S;
11     update D(v) for all v adjacent
         to w and not in S:
12     If D(w) + c(w,v) < D(v) then
       D(v) = D(w) + c(w,v); p(v) = w;
13  until all nodes in S;
```

Example: Dijkstra's Algorithm

Step	start S	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1	AD		4,D		2,D	
2	ADE		3,E			4,E
3	ADEB					
4	ADEBC					
5	ADEBCF					



…

Loop

  find **w** not in **S** s.t. D(w) is a minimum;

  add **w** to **S**;

  update D(v) for all **v** adjacent to **w** and not in **S**:

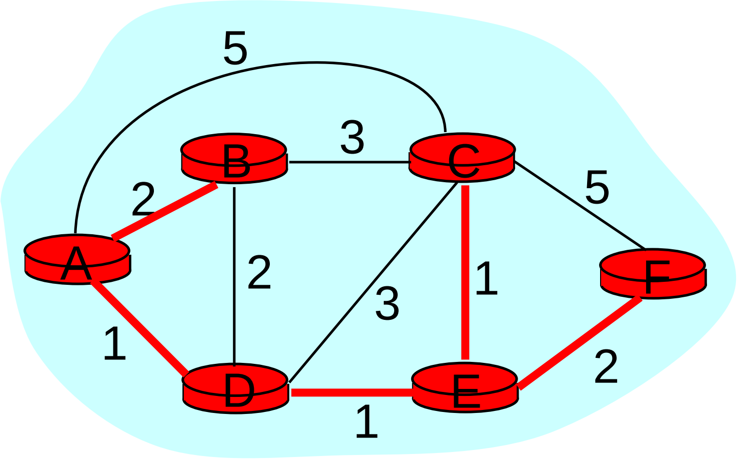
  If D(w) + c(w,v) < D(v) then

    D(v) = D(w) + c(w,v); p(v) = w;

until all nodes in S;

Example: Dijkstra's Algorithm

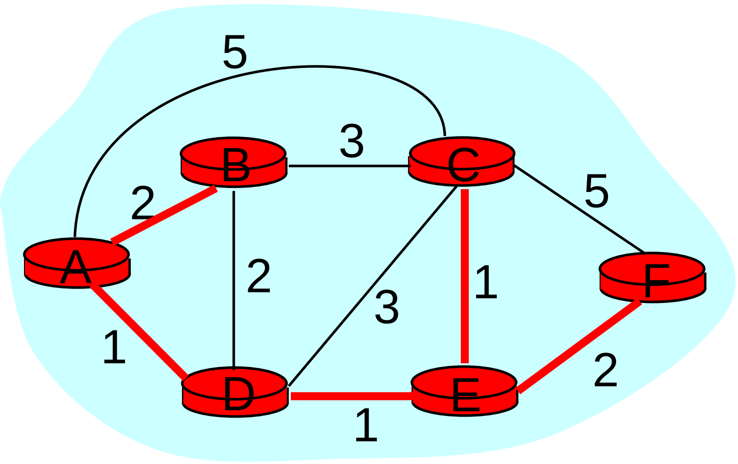
Step	start S	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	∞	∞
1	AD		4,D		2,D	
2	ADE		3,E			4,E
3	ADEB					
4	ADEBC					
5	ADEBCF					



To determine path A $\rightarrow$ C (say), work backward from C via p(v)

The Forwarding Table

- Running Dijkstra at node *A* gives the shortest path from *A* to all destinations
- We then construct the *forwarding* table



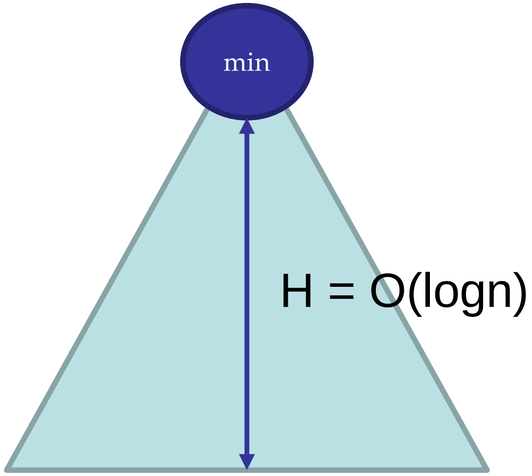
Destination	Link
B	(A,B)
C	(A,D)
D	(A,D)
E	(A,D)
F	(A,D)

Subnet address (CIDRised) and interface

Dijkstra's algorithm, discussion

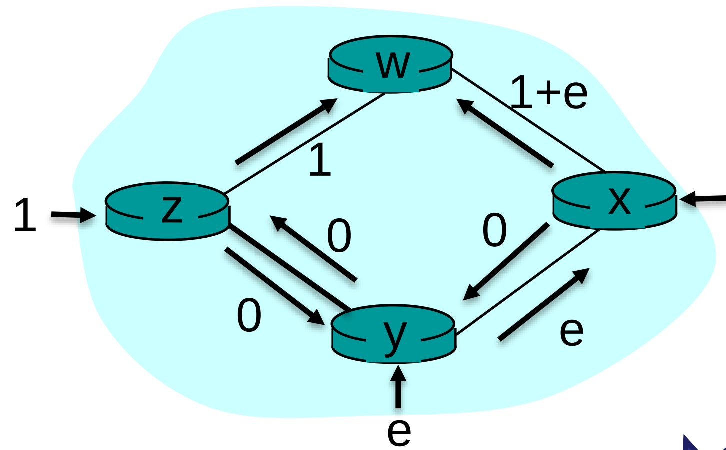
Algorithm complexity: n nodes

- each iteration: need to check all nodes, w, not in N
- n(n-1)/2 comparisons: $O(n^2)$
- more efficient implementations possible: O(nlogn)
  - Using a min-heap;
  - we can find out the node with min cost in O(logn);
  - Total cost = O(log(n-1) + log(n-2) + … + log1) = O(log(n!))
  - = O(nlogn) (using *Stirling's approximation*).

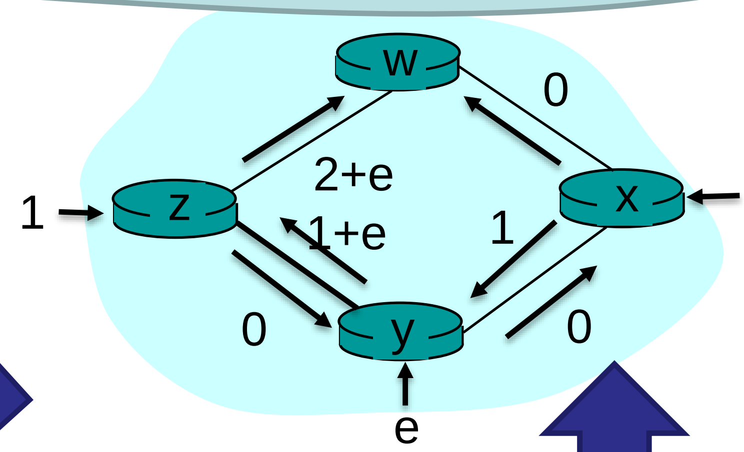


Oscillation with link-state routing

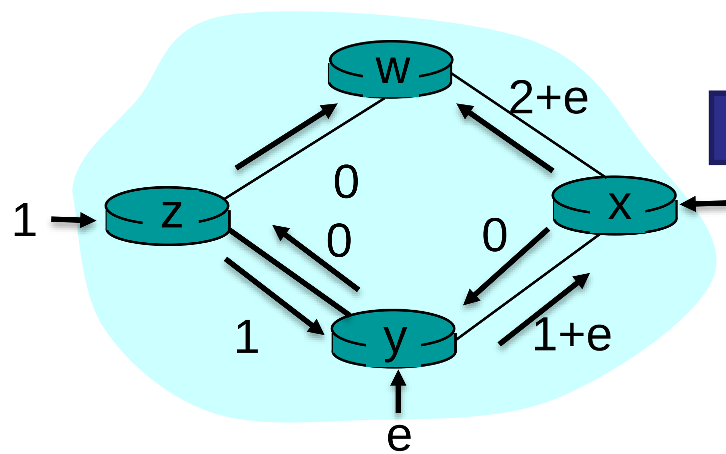
Today's Internet routing algorithms are load-*insensitive*!



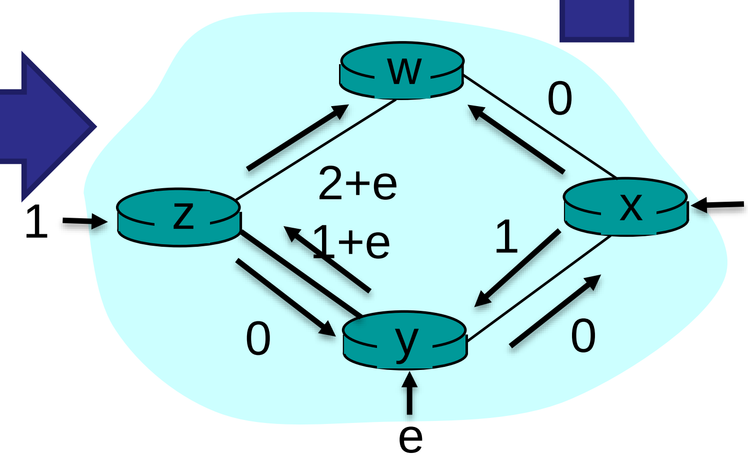
a. Initial routing



b. x,y detect better path to w, ckwise



c. x, y, z detect better path to w, counterclockwise



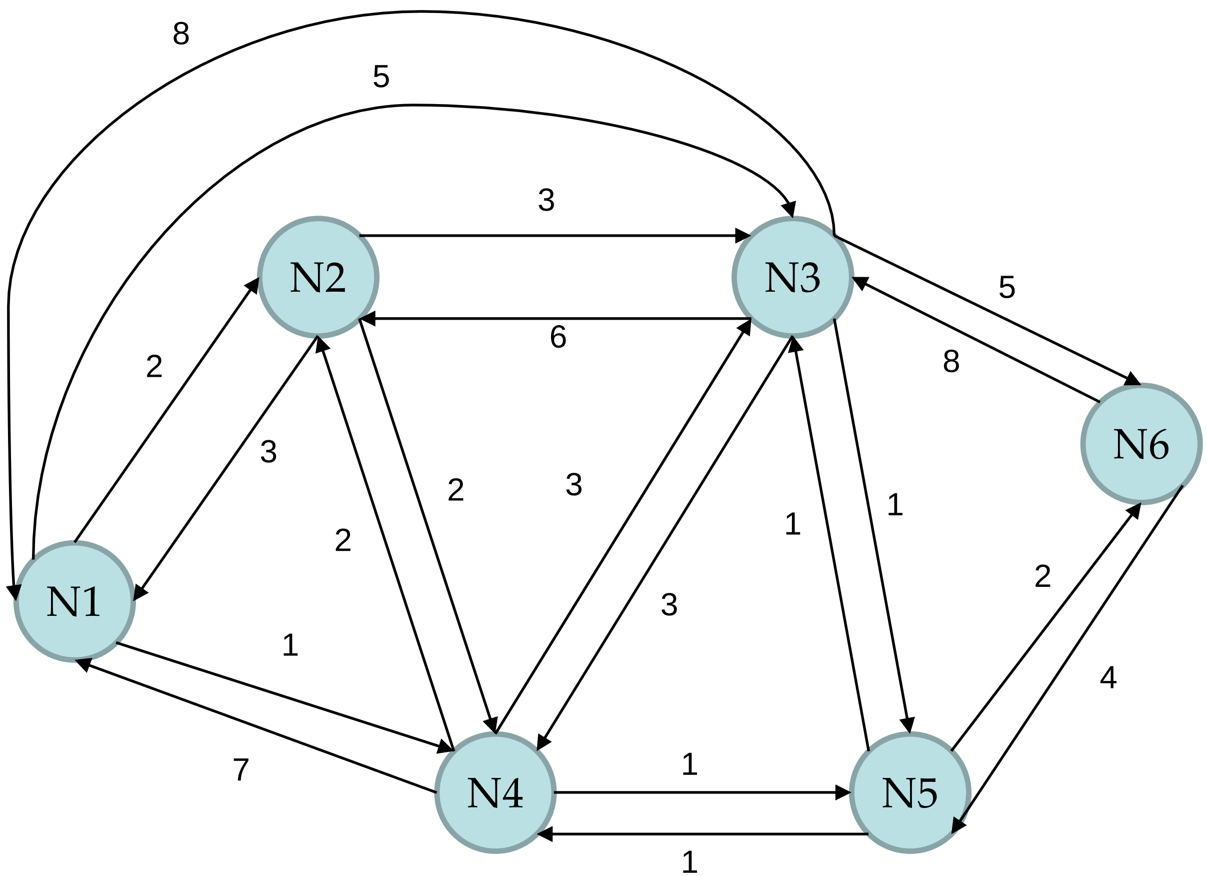
d. x,y,z detect better path to w, clockwise

Summary: Link-State Routing

- Each router broadcasts the link state
  - To give every router a complete view of the graph
- Each router runs Dijkstra's algorithm
  - Compute least-cost paths, then construct forwarding table

Exercise

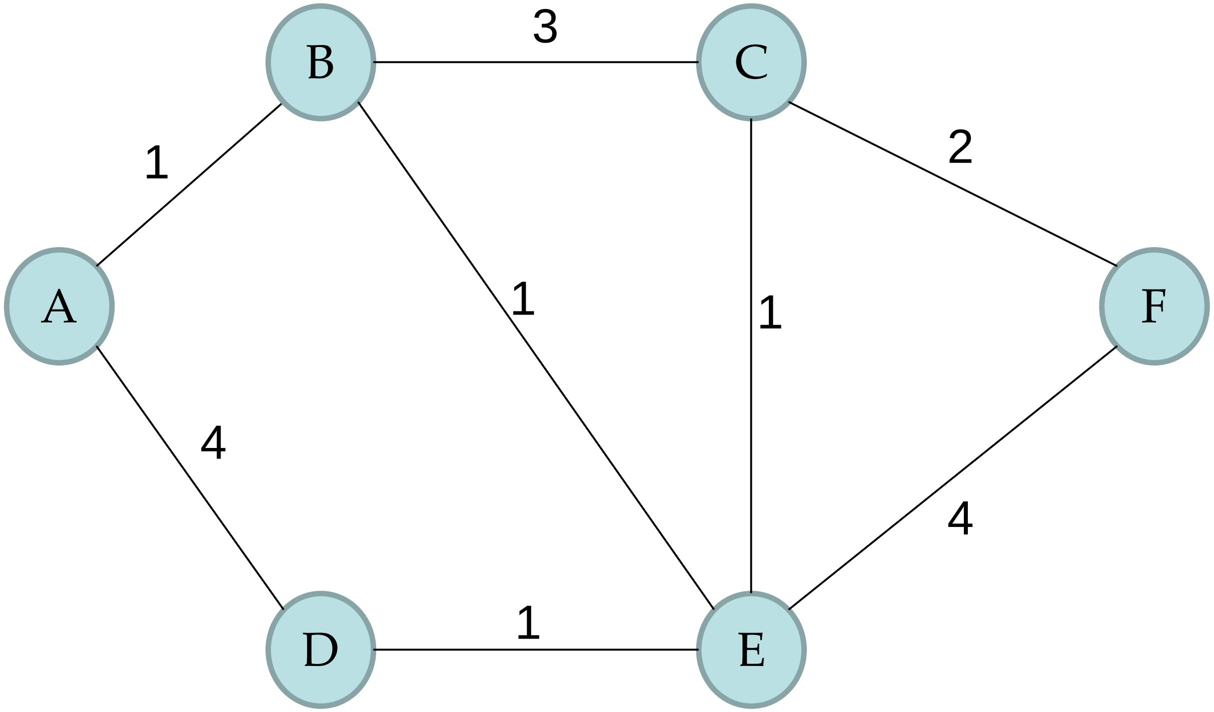
Example net. 1 (Fig. 19.1 W. Stallings' book)



Dijkstra’s algorithm (for node 1)

step	S	D(2), p(2)	D(3), p(3)	D(4), p(4)	D(5), p(5)	D(6), p(6)
0	{1}	2,1	5,1	1,1	inf	inf
1	{1,4}	2,1	4, 4	1,1	2,4	inf
2	{1,4,2}	2,1	4, 4	1,1	2,4	inf
3	{1,4,2,5}	2,1	3,5	1,1	2,4	4,5
4	{1,4,2,5,3}	2,1	3,5	1,1	2,4	4,5
5	{1,4,2,5,3 6}	2,1	3,5	1,1	2,4	4,5

Example net 2



Dijkstra's algorithm (for node A)

step	S	D(B), p(B)	D(C), p(C)	D(D), p(D)	D(E), p(E)	D(F), p(F)
0	{A}	1,A	inf	4,A	inf	inf
1	{A,B}	1,A	4,B	4,A	2,B	inf
2	{A,B,E}	1,A	3,E	3,E	2,B	6,E
3	{A,B,E,D}	1,A	3,E	3,E	2,B	6,E **
4	{A,B,E,D, C}	1,A	3,E	3,E	2,B	5, C
5	{A,B,E,D, C,F}	1,A	3,E	3,E	2,B	5, C

**6,E will be 5, C if node C is chosen first.

References

- [KR3] James F. Kurose, Keith W. Ross, *Computer networking: a top-down approach featuring the Internet*, 3rd edition.
- [PD5] Larry L. Peterson, Bruce S. Davie, *Computer networks: a systems approach*, 5th edition
- [TW5] Andrew S. Tanenbaum, David J. Wetherall, *Computer network*, 5th edition
- [LHBi]Y-D. Lin, R-H. Hwang, F. Baker, *Computer network: an open source approach*, International edition

Acknowledgements

- All slides are developed based on slides from the following two sources:
  - Dr DongSeong Kim's slides for COSC264, University of Canterbury;
  - Prof Aleksandar Kuzmanovic's lecture notes for CS340,Northwestern University, https://users.cs.northwestern.edu/~akuzma/classes/CS340-w05/lecture_notes.htm