SC250
Computer Networking I

Network Layer Principles

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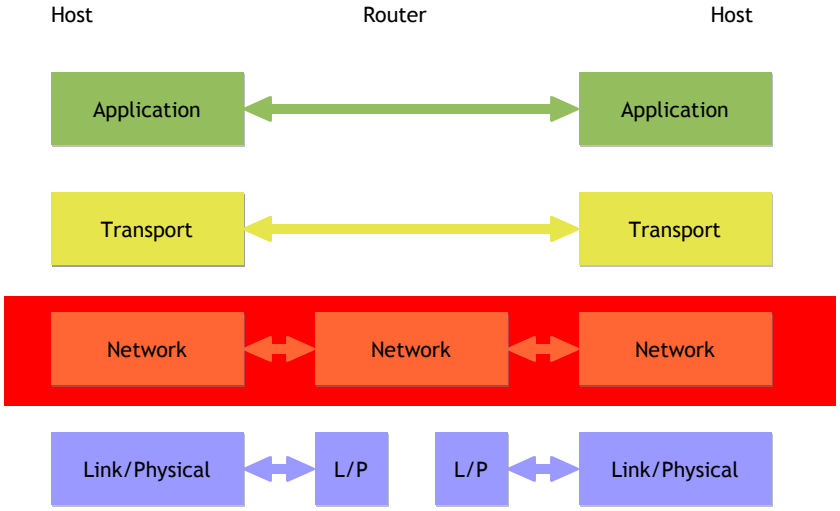
Network Layer



Objectives

- Understand principles behind network layer services:
  - Routing (path selection)
  - Dealing with scale: routing hierarchy and autonomous systems (AS)
- Instantiation and implementation in the Internet
  - Next week

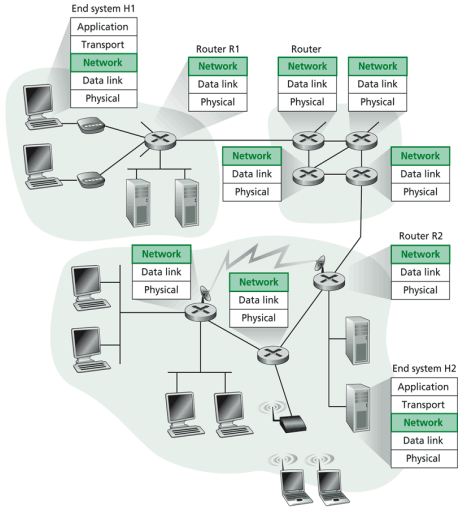
- Overview:
  - Today:
    - network layer services
    - routing principles:
      - path selection
      - hierarchical routing
  - Next week:
    - IP protocol
    - Internet routing protocols
      - intra-domain
      - inter-domain

Network Layer Functions

- Transport packet from sending to receiving hosts
- Network layer protocols in *every* host, router

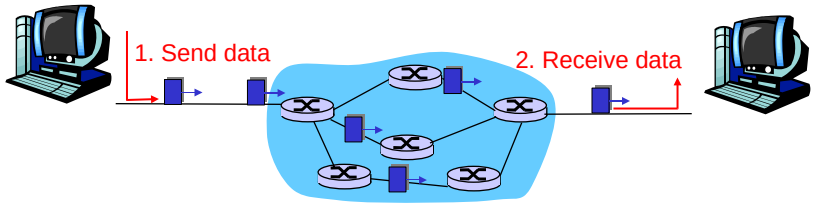
Three important functions:

- *Path determination:* route taken by packets from source to dest. *Routing algorithms*
- *Forwarding:* move packets from router's input to appropriate router output
- *Call/circuit setup:* some network architectures require router call setup along path before data flows



Datagram Networks: The Internet Model

- No call setup at network layer
- Routers: no state about end-to-end connections
  - no network-level concept of "connection"
- Packets forwarded using destination host address
  - packets between same source-dest pair may take different paths



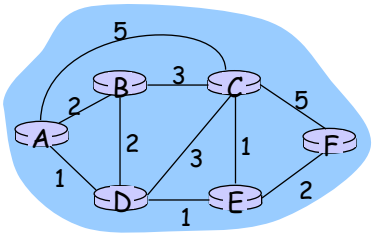
Routing

Routing protocol:

Goal: determine "good" path (sequence of routers) through network from source to destination

Graph abstraction for routing algorithms:

- Graph nodes are routers
- Graph edges are physical links
  - link cost: delay, $ cost, or congestion level



- "Good" path:
  - typically means minimum cost path
  - other definitions possible

Routing Algorithm Classification

- Global or decentralized information?
  - Global:
    - all routers have complete topology, link cost info
    - "link state" algorithms
  - Decentralized:
    - router knows physically-connected neighbors, link costs to neighbors
    - iterative process of computation, exchange of info with neighbors
    - "distance vector" algorithms
- Static or dynamic?
  - Static:
    - routes change slowly over time
  - Dynamic:
    - routes change more quickly
      - periodic update
      - in response to link cost changes

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 routing table for that node
- Iterative: after k iterations, know least cost path to k destinations

Notation:

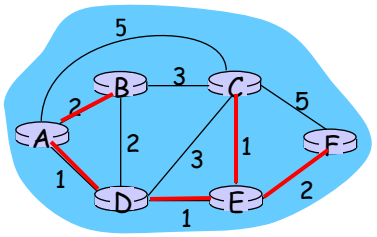
- c(i,j): link cost from node i to j. cost infinite if not direct neighbors
- D(v): current value of cost of path from source to dest. V
- p(v): predecessor node along path from source to v, that is next v
- N: set of nodes whose least cost path definitively known

Dijkstra's Algorithm

```
1  Initialization:
2    N = {A}
3    for all nodes v
4      if v adjacent to A
5        then D(v) = c(A,v)
6        else D(v) = infinity
7
8  Loop
9    find w not in N such that D(w) is a minimum
10   add w to N
11   update D(v) for all v adjacent to w and not in N:
12      D(v) = min( D(v), D(w) + c(w,v) )
13   /* new cost to v is either old cost to v or known
14    shortest path cost to w plus cost from w to v */
15 until all nodes in N
```


Dijkstra's Algorithm: Example

Step	start N	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,A	4,D		2,D	∞
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					



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(n log n)

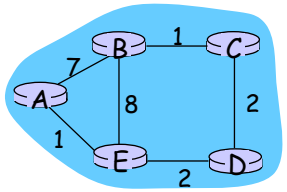
Distance Vector Routing Algorithm

- Iterative:
  - Continues until no nodes exchange info.
  - Self-terminating: no "signal" to stop
- Asynchronous:
  - Nodes need not exchange info/iterate in lock step!
- Distributed:
  - Each node communicates only with directly-attached neighbors
- Distance Table data structure
  - Each node has its own
  - Row for each possible destination
  - Column for each directly-attached neighbor to node
- Example: in node X, for dest. Y via neighbor Z:

$D^X(Y,Z)$ = distance *from* X *to* Y, *via* Z as next hop

$= c(X,Z) + \min_w \{D^Z(Y,w)\}$

Distance Table: Example



$D^E(C,D) = c(E,D) + \min_w \{D^D(C,w)\}$
$= 2+2 = 4$

$D^E(A,D) = c(E,D) + \min_w \{D^D(A,w)\}$
$= 2+3 = 5$ loop!

$D^E(A,B) = c(E,B) + \min_w \{D^B(A,w)\}$
$= 8+6 = 14$ loop!

cost to destination via

destination	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

Distance Table Gives Forwarding Table

cost to destination via

destination	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

Outgoing link to use, cost

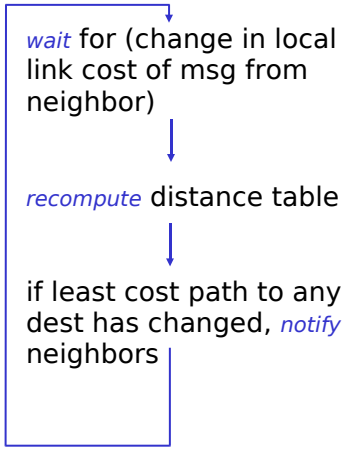
destination	
A	A,1
B	D,5
C	D,4
D	D,4

Distance table → Forwarding table

Distance Vector Routing: Overview

- Iterative, asynchronous:
  - each local iteration caused by:
    - local link cost change
    - message from neighbor: its least cost path change from neighbor
- Distributed:
  - each node notifies neighbors only when its least cost path to any destination changes
  - neighbors then notify their neighbors if necessary

Each node:



Distance Vector Algorithm

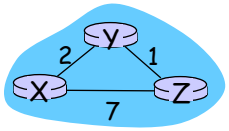
At all nodes X:

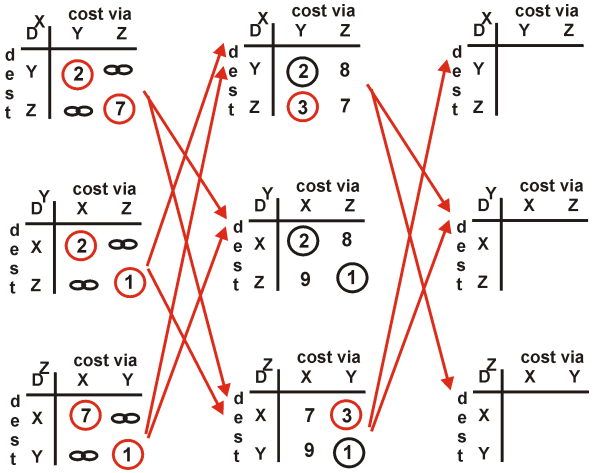
```
1  Initialization:
2   for all adjacent nodes v:
3     D^X(*,v) = infinity       /* the * operator means "for all rows" */
4     D^X(v,v) = c(X,v)
5   for all destinations, y
6     send min_w D^X(y,w) to each neighbor  /* w over all X's neighbors */
```

Distance Vector Algorithm (more)

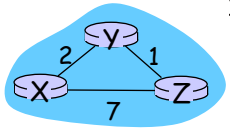
```
8  loop
9    wait (until I see a link cost change to neighbor V
10         or until I receive update from neighbor V)
11
12   if (c(X,V) changes by d)
13     /* change cost to all dest's via neighbor v by d */
14     /* note: d could be positive or negative */
15     for all destinations y:  D^X(y,V) =  D^X(y,V) + d
16
17   else if (update received from V wrt destination Y)
18     /* shortest path from V to some Y has changed  */
19     /* V has sent a new value for its  min_w  D^V(Y,w) */
20     /* call this received new value is "newval"     */
21     for the single destination y: D^X (Y,V) = c(X,V) + newval
22
23   if we have a new min_w D^X (Y,w)for any destination Y
24      send new value of min_w D^X (Y,w) to all neighbors
25
26 forever
```

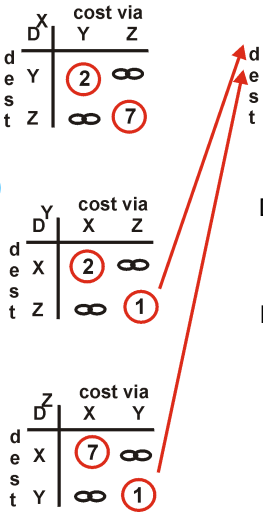

Distance Vector Algorithm: Example





Distance Vector Algorithm: Example





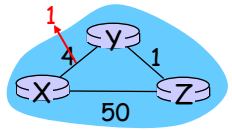
$D^X(Y,Z) = c(X,Z) + \min_w \{D^Z(Y,w)\}$
$= 7+1 = 8$

$D^X(Z,Y) = c(X,Y) + \min_w \{D^Y(Z,w)\}$
$= 2+1 = 3$

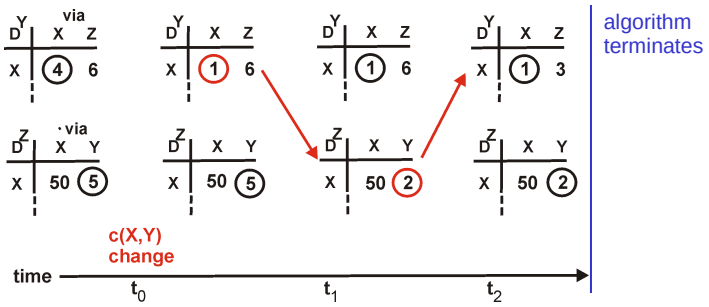
Distance Vector: Link Cost Changes

Link cost changes:

- node detects local link cost change
- updates distance table (line 15)
- if cost change in least cost path, notify neighbors (lines 23,24)



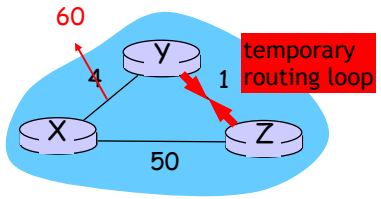
"good news travels fast"

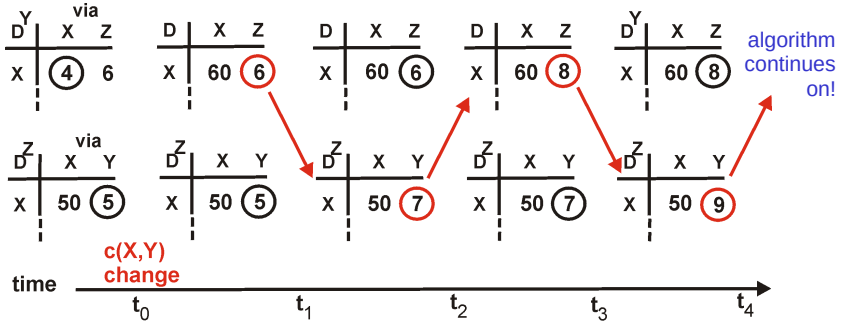


Distance Vector: Link Cost Changes

Link cost changes:

- good news travels fast
- bad news travels slow - **"count to infinity" problem!**

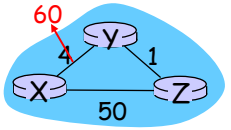


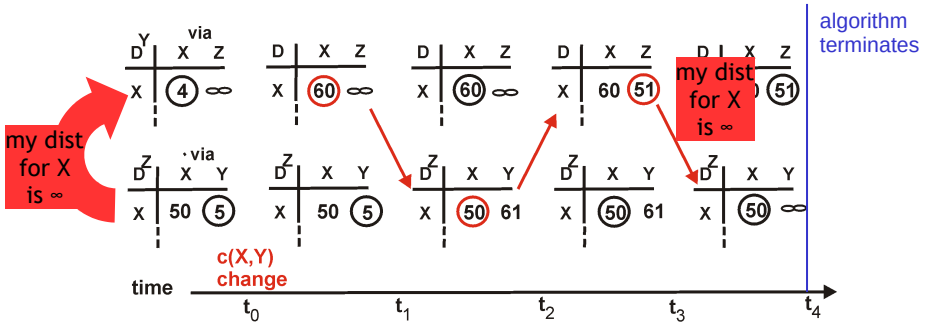


DV Count-to-∞: Poisoned Reverse

If Z routes through Y to get to X :

- Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z)
- Will this completely solve count to infinity problem?





Comparison of LS and DV Algorithms

- Message complexity
  - LS: with n nodes, E links, O(nE) msgs sent each
  - 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-∞ 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
      - errors propagate through network

Summary: Routing Principles

- Network layer service model:
  - Host-to-host datagram service
  - Best-effort
- Routing algorithms
  - Link-state: Dijkstra
    - centralized algorithm to compute shortest-path tree to/from a vertex
  - Distance-vector: Bellman-Ford
    - distributed algorithm to compute all shortest paths