The Network Layer

Introduction

- functionality and service models

Theory

- link state and distance vector algorithms
- broadcast algorithms
- hierarchical routing

The Network Layer (cont)

Case Study: IP

- services
- packet formats, addressing
- routing protocols: RIP, OSPF, BGP
- ICMP
- IPV6

Case Study: ATM

- services
- cell formats
- VP's and VC's

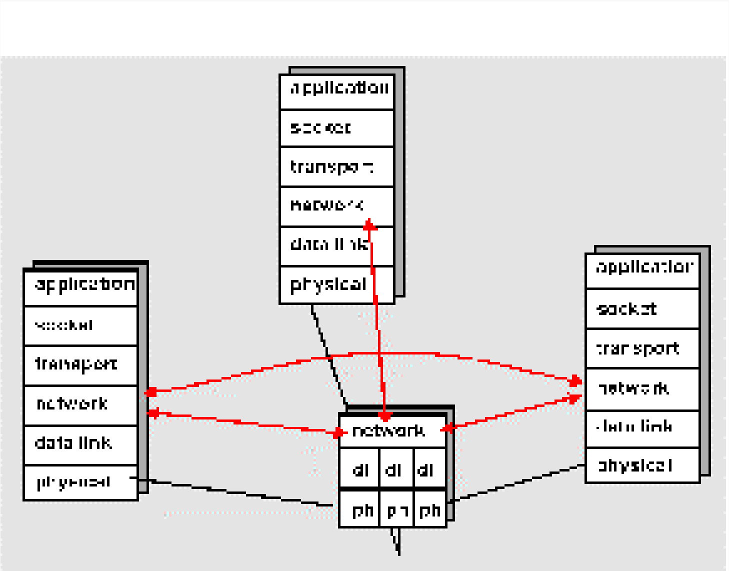
The Network Layer (cont)

Routers and Switches

how they work

Readings

- Tannenbaum: 5.1, 5.2, 5.4-5.7
- Kurose Ross: ch 4



Network Layer: Introduction

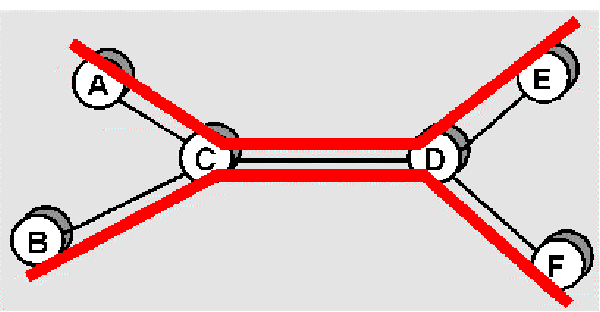
Network layer: *a network-wide* concern

- *transport layer:* between two hosts
- *data link layer:* between two physically connected hosts, routers
- *network layer*: involves each and every router, host, gateway in the network

Network Layer Service: Virtual Circuit

Virtual: looks like a circuit but isn't

- generally associated with connection-oriented service
- all packets within connection follow same route



At connection establishment time:

- connection setup packet flows from sender to receiver
- routing tables updated at intermediate nodes to reflect new VC
- **key issue:** per-connection state at router
- fits well with QoS guarantees: reserve resources and/or accept/reject call based on resources at this router

Analogy: telephone network

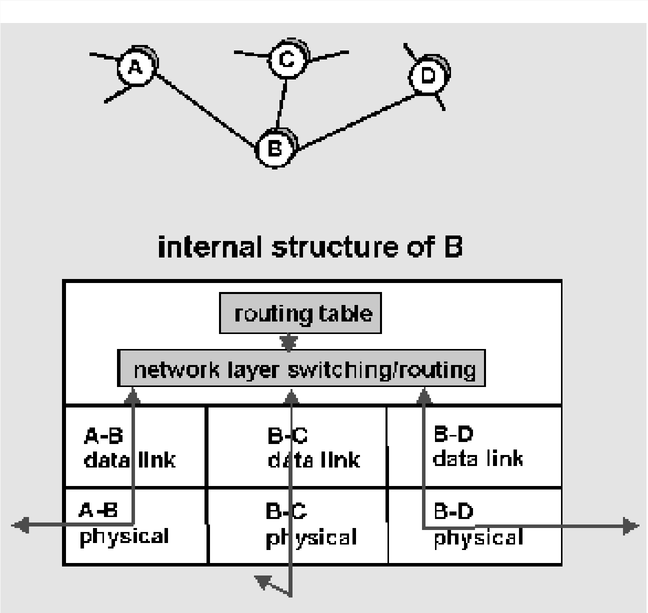
Network Layer Service: datagrams

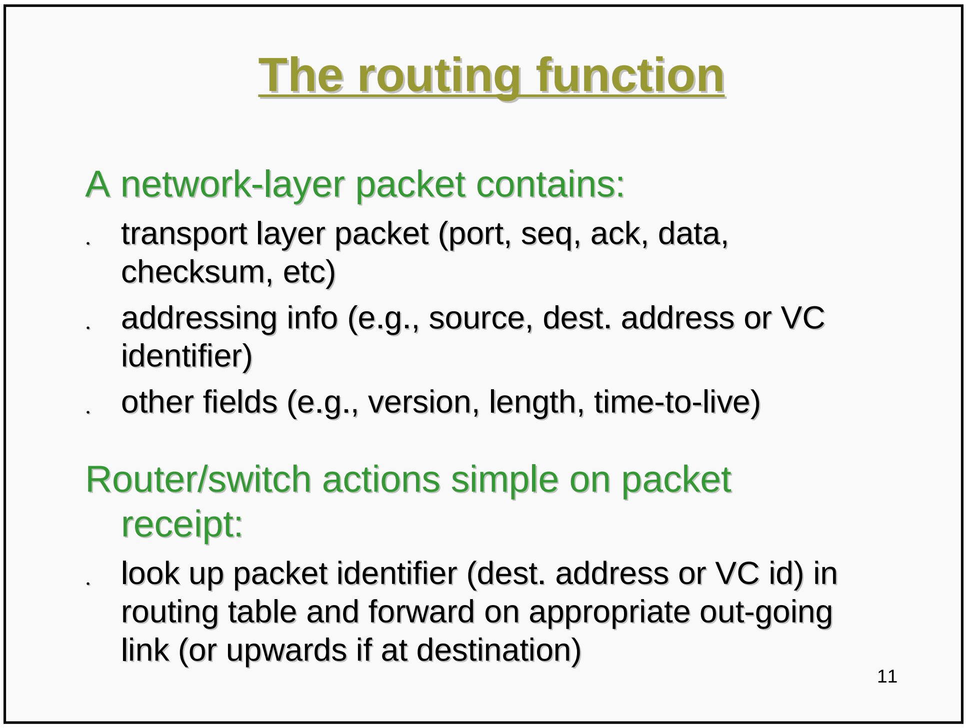
- no notion of connection in network layer
- no routes set up at connection establishment time - each packet in "connection" may follow different path
- no guarantee of reliable, or in-order delivery
- advantages:
    - no connection state in routers
    - robust with respect to link failures
    - recovery at end-systems (transport level)

Burning question: to VC or not to VC?

Answer: support both, offering different service models:

- best effort service: datagrams
- service with performance guarantees: QOS





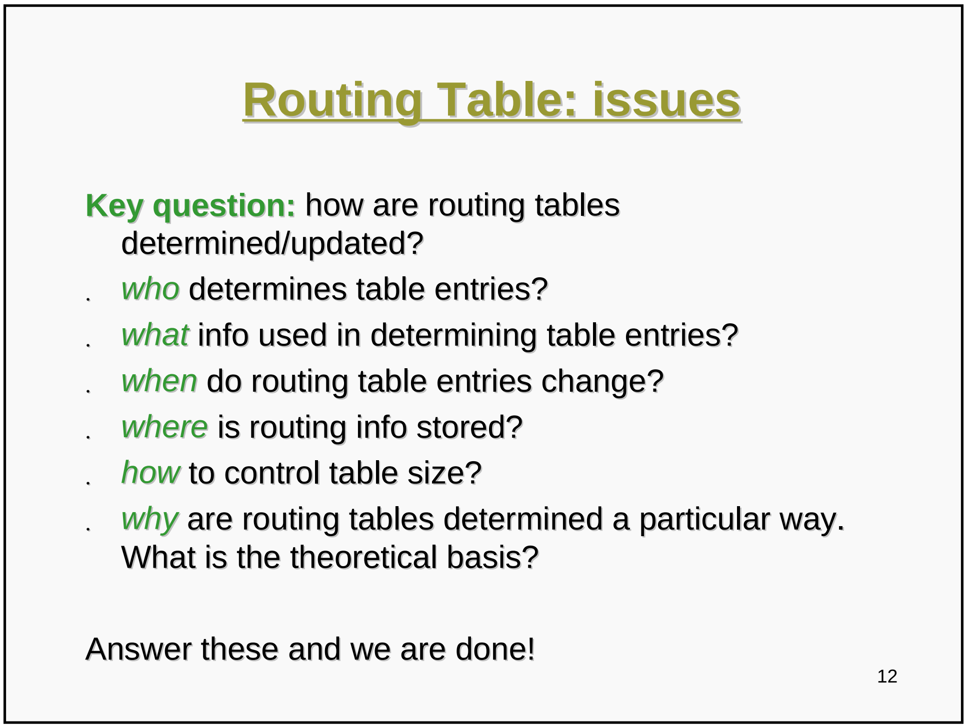
The routing function

A network-layer packet contains:

- transport layer packet (port, seq, ack, data, checksum, etc)
- addressing info (e.g., source, dest. address or VC identifier)
- other fields (e.g., version, length, time-to-live)

Router/switch actions simple on packet receipt:

- look up packet identifier (dest. address or VC id) in routing table and forward on appropriate out-going link (or upwards if at destination)



Routing Table: issues

Key question: how are routing tables determined/updated?

- *who* determines table entries?
- *what* info used in determining table entries?
- *when* do routing table entries change?
- *where* is routing info stored?
- *how* to control table size?
- *why* are routing tables determined a particular way. What is the theoretical basis?

Answer these and we are done!

Routing issues:

- **scalability:** must be able to support large numbers of hosts, routers, networks
- **adapt** to changes in topology or significant changes in traffic, **quickly** and **efficiently**
  - self-healing: little or not human intervention
- route selection may depend on different criteria
- **performance:** "choose route with smallest delay"
- **policy:** "choose a route that doesn't cross a government network" (equivalently: "let no non-government traffic cross this network")

Classification of Routing Algorithms

Centralized versus decentralized

- **centralized:** central site computes and distributed routes (equivalently: information for computing routes known globally, each router makes same computation)
- **decentralized:** each router sees only local information (itself and physically-connected neighbors) and computes routes on this basis
- pros and cons?

Classification (cont)

Static versus adaptive

- **static:** routing tables change very slowly, often in response to human intervention
- **dynamic:** routing tables change as network traffic or topology change
- pros and cons?

Two basic approaches adopted in practice:

- **link-state routing:** centralized, dynamic (periodically run)
- **distance vector:** distributed, dynamic (in direct response to changes)

Link-state routing

- each node knows network topology and cost of each link
  - quasi-centralized: each router periodically broadcasts costs of attached links
- cost may reflect
  - queueing delay on link
  - link bandwidth
  - all links with equal cost: shortest path routes
- used in Internet OSPF, ISO IS-IS, DECnet, "new" (1980) ARPAnet routing algorithm

Goal: find least cost path from one node (source) to all other nodes

- Dijkstra's shortest path algorithm

Dijkstra's Shortest Path Algorithm: Definitions

Define:

c(i,j): cost of link from *i*-to-*j*. *c(i,j)* = infty if *i,j* not directly connected. We will assume *c(i,j)* equals *c(j,i)* but not always true in practice

D(v): cost of currently known least cost path from source, *A,* to node *v*.

p(v): previous node (neighbor of *v*) along current shortest path from source to *v*

N: set of nodes whose shortest path from *A* is definitively known

Iterative: after *k* iterations, know paths to *k* "closest" (path cost) to *A*

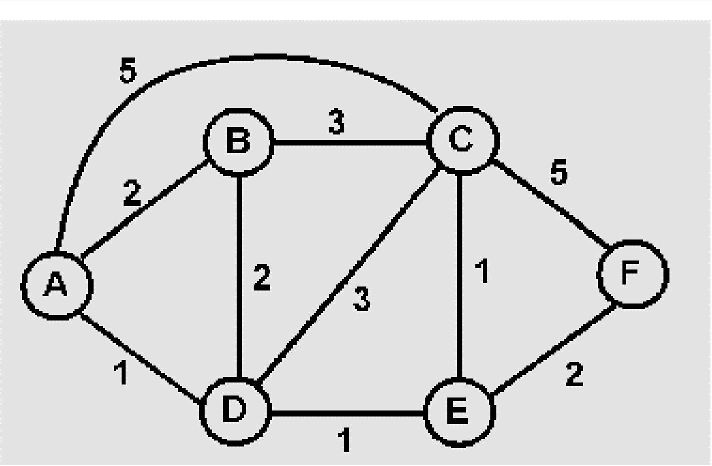
Dijkstra's algorithm: Statement

Initialization:

```
N = {A}
for all nodes v
    if v adjacent to A then D(v) = c(A,v)
                        else D(v) = infty
```

Loop:

```
find w not in N such that D(w) is a minimum
add w to N
update D(v) for all v 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
```



step	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	Infty	Infty
1	AD	2,A	4,D		2,D	infty
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					

- example: in step 1: D(C) = D(D)+c(D,C)

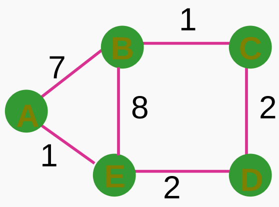
  1 + 3
- for each column, last entry gives immediate neighbor on least cost path to/from A, and cost to that node
- worst case running time: O(N^2)

Distance vector routing

Asynchronous, iterative, distributed computation:

- much more fun!
- at each step:
  - receive info from neighbor or notice change in local link cost
  - compute
  - possibly send new info to adjacent neighbors

Computation/communication between network layer entities!



cost to dest. via

destination

$D_E()$	A	B	D
A	**1**	14	5
B	7	8	**5**
C	6	9	**4**
D	4	11	**2**

Distance table:

- per-node table recording cost to all other nodes via each of its neighbors
- $D_E(A,B)$ gives minimum cost from E to A given that first node on path is B
  - $D_E(A,B) = c(E,B) + \min D_B(A,*)$
  - $\min D_E(A,*)$ gives E's minimum cost to A
  - routing table derived from distance table
- example: $D_E(A,B) = 14$ (note: not 15!)
- example: $D_E(C,D) = 4$, $D_E(C,A) = 6$

Distance vector algorithm

- based on Bellman-Ford algorithm
- used in many routing protocols: Internet BGP, ISO IDRP, Novell IPX, original ARPAnet

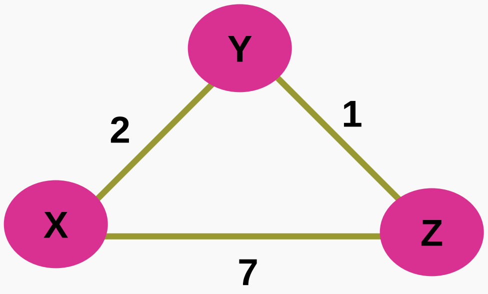
Algorithm (at node X):

Initialization: for all adjacent nodes v:
D(*,v) = infty
D(v,v) = c(X,v)
send shortest path cost to each destination to neighbors
Loop:
execute distributed topology update algorithm
forever

Update Algorithm at Node X:

```
1. wait (until I see a link cost change to neighbor Y
    or until receive update from neighbor W)
2. if (c(X,Y) changes by delta) {
     /* change my cost to my neighbor Y */
change all column-Y entries in distance table by delta
if this changes my least cost path to Z
send update wrt Z, $D_x(Z,*)$ , to all neighbors
 }
3. if (update received from W wrt Z) {
/* shortest path from W to some Z has changed */
    $D_x(Z,W) = c(X,W) + D_w(Z,*)$ }
if this changes my least cost path to Z
send update wrt Z, $D_x(Z,*)$ , to all neighbors
```

Distance Vector Routing: Example



D_X	Y	Z
Y	**2**	infty
Z	infty	**7**

D_X	Y	Z
Y		
Z		

D_X	Y	Z
Y		
Z		

D_Y	X	Z
X	**2**	infty
Z	infty	**1**

D_Y	X	Z
X		
Z		

D_Y	X	Z
X		
Z		

D_Z	X	Y
X	**7**	infty
Y	infty	**1**

D_Z	X	Y
X		
Y		

D_Z	X	Y
X		
Y		

Distance Vector Routing: Recovery from Link Failure

- if link XY fails, set c(X,Y) to infty and run topology update algorithm
- example (next page)
- good news travels fast, bad news travels slow
- **looping:**
  - inconsistent routing tables: to get to A, D routes through E, but E routes through D
  - loops eventually disappear (after enough iterations)
  - loops result in performance degradation, out-of-order delivery

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Distance Vector Routing: Example of Recovery

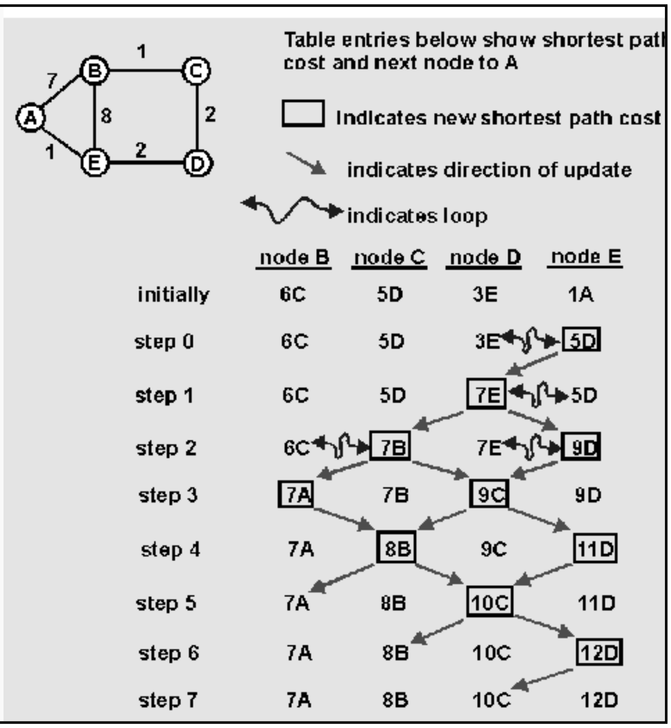


Table entries below show shortest patl cost and next node to A

☐ Indicates new shortest path cost

↘ indicates direction of update

↔ indicates loop

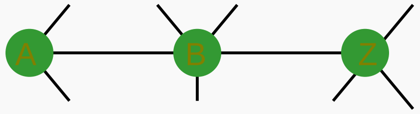
	node B	node C	node D	node E
initially	6C	5D	3E	1A
step 0	6C	5D	3E	5D
step 1	6C	5D	7E	5D
step 2	6C	7B	7E	9D
step 3	7A	7B	9C	9D
step 4	7A	8B	9C	11D
step 5	7A	8B	10C	11D
step 6	7A	8B	10C	12D
step 7	7A	8B	10C	12D

Distance Vector Routing: Solving the Looping Problem

Count to infinity problem: loops will exist in tables until table values "count up" to cost of alternate route

Split Horizon Algorithm:

- rule: if A routes traffic to Z via B then A tells B its distance to Z is infinity
- example: B will never route its traffic to Z via A
- does not solve the count to infinity problem (why)?



More problems: Oscillations

A reasonable scenario

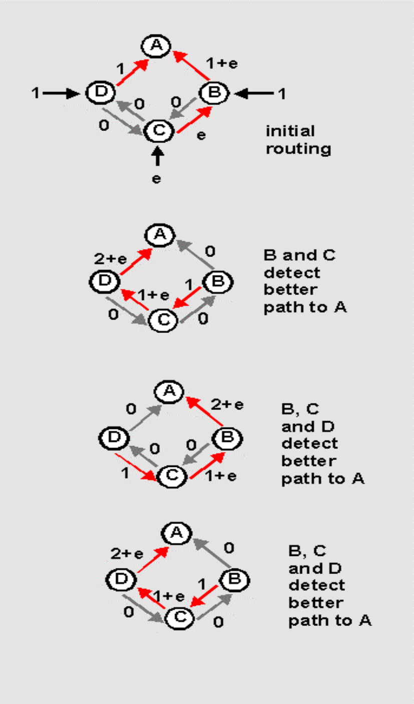
- cost of link depends on amount of traffic carried
- nodes exchange link costs every T
- suppose:
  - A is destination for all traffic
  - B,D send 1 unit of traffic to A
  - C sends e units of traffic (e<<1) to A

Entire network may "oscillate"

Possible solutions:

- avoid periodic exchange (randomization)
- don't let link costs be increasing functions of load

Distance Vector Oscillations



Comparison of LS and DV algorithms

Message complexity:

- **"LS is better":** DV requires iteration with msg exchange at each iteration
- **"DV is better":** if link changes don't affect shortest cost path, no msg exchange

Robustness: what happens if router fails, misbehaves or is sabotaged?

LS could :

- report incorrect distance to connected neighbors
- corrupt/lose any LS broadcast msgs passing through
- report incorrect neighbor

DV could:

- advertise incorrect shortest path costs to any/all destinations (caused ARPAnet crash: "I have zero cost to everyone")

Comparison of LS and DV (cont)

Speed of convergence

DV:

- may iterate many times while converging
- loops, count-to-infinity, oscillations
- cannot propagate new info until recomputes its own routes

LS:

- requires 1 broadcast per node per recomputation
- can suffer from oscillations

both have strengths and weakness

- one or the other used in almost every network

2nd Try (at LS Broadcast Distribution)

Each router puts a sequence number on its LSP's

- upon receiving LSP(R) from R

```
if (seq # > seq # of stored copy ) of LSP(R)
    then store LSP(R), update LS info for R, and flood LSP(R)
    else ignore duplicate
```

How can this protocol fail?