WANs and Long Distance Connectivity

Chapters 12-13

Introduction

- Previous technologies covered "short" distances
  - Can extend over short distances somewhat with bridges, hubs, repeaters, etc. but still limited
  - We need to cover longer distances - e.g. Anchorage to Seattle
- Will call this technology *WAN* - *W*ide *A*rea *N*etwork
- Two categories:
  - Long distance between networks
  - "Local loop" - the copper between the Telco's CO and the subscriber (e.g., home)

Digital Telephony

- Analog used in olden days throughout the telco
  - Problem of amplifying noise, distortion
- Telco uses digital technology today
  - Thanks in large part to fiber optics
  - High initial cost in conversion
  - Benefit of packet switched technology, reduced problems with noise
- Voice digitized and sent digitally
  - Recall PCM : Pulse Code Modulation
  - 8000 samples per second (twice the bandwidth), each sample value 0-255
  - Requires 64Kbps throughput to transmit digitized voice

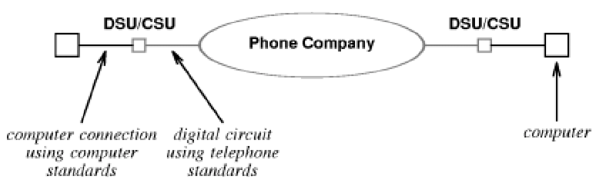
Synchronous Communications

- Telephone Network uses synchronous communications
  - Converting back to audio requires data be available "on time"
  - Digital telephony systems use *clocking* for *synchronous* data delivery
  - Samples not delayed as traffic increases
  - Telephone system carefully designed so the rate of data on receiver is the same as the rate that it entered
    - Consider understanding a voice call if these rates were different!

Digital Circuits and Computer Data

- So, digital telephony can handle synchronous data delivery
  - Can we use that for data delivery?
  - Ethernet frame != 8-bit PCM synchronous
  - Need to convert formats...
- To use digital telephony for data delivery:
  - Lease *point-to-point digital circuit* between sites
  - Convert between local and PCM formats at each end
- Use a *Data Service Unit/Channel Service Unit* (DSU/CSU) at each end
  - CSU - manages control functions
  - DSU - converts data
  - Telco analogy to a modem

Using a CSU/DSU



Many different CSU/DSU's out there, supporting different protocols

Telephone Standards

- Most common standard is the T-series
- European standards start with E
- The T standard doesn't specify the physical media
  - Could use satellite, copper, fiber, etc.
  - Specifies data rates, multiplexing is common

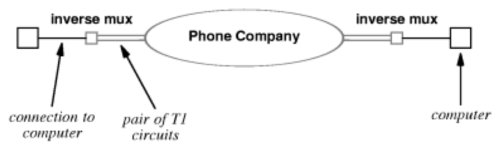
	Name	Bit Rate	Voice Circuits	Location
	ISDN	0.064Mbps	1	
	T1	1.544Mbps	24	NA
	T2	6.312Mbps	96	NA
28 T1's	T3	44.736Mbps	672	NA
	E1	2.048Mbps	30	Europe
	E2	8.448Mbps	120	Europe
	E3	34.368Mbps	480	Europe

Terminology and Variations

- T standard technically different than DS standard, although the terms are used interchangeably in practice
- DS = Digital Signal Level Standards
  - DS1 = digital service that can multiplex 24 calls into a single circuit
  - i.e. T1 speeds
  - Most popular are T1 and T3, or DS1 and DS3
- What if you don't want an entire T1?
  - Expensive, generally too much for individuals
  - Fractional T1 is an option
    - Lease capacity in chunks of 64K, e.g. 128Kbps, or 56Kbps too
    - Phone company uses TDM to subdivide the T1 circuit

Intermediate Capacity

- Price does not go up linearly with speed
  - $$ for T3 < $$ for 28 * T1
    ...however, if all you need is 9 Mbps, $$ for T3 > $$ for 6 * T1
- Solution: combine multiple T1 lines with *inverse multiplexor*



Some CSU/DSU's are able to support inverse multiplexing

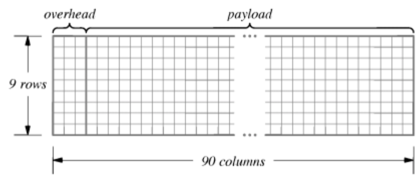
Higher Capacity Circuits

- A trunk denotes a high-capacity circuit
- STS = Synchronous Transport Signal
  - Refers to electrical signals used in the digital circuit interface
- OC = Optical Carrier
  - Refers to optical signals over fiber
  - Distinction often lost in the field to STS
  - *C* suffix indicates *concatenated*:
    - OC-3 == three OC-1 circuits at 51.84 Mbps
    - OC-3C == one 155.52 Mbps circuit

Standard name	Optical name	Bit rate	Voice circuits
STS-1	OC-1	51.840 Mbps	810
STS-3	OC-3	155.520 Mbps	2,430
STS-12	OC-12	622.080 Mbps	9,720
STS-24	OC-24	1,244.160 Mbps	19,440
STS-48	OC-48	2,488.320 Mbps	38,880

SONET

- *Synchronous Optical Network* (SONET) defines how to use high-speed connections
  - Framing: STS-1 uses 810 bytes per frame
  - Encoding: Each sample travels as one octet in payload
- Payload changes with data rate
  - STS-1 transmits 6,480 bits in 125 microseconds (== 810 octets)
  - STS-3 transmits 19,440 bits in 125 microseconds (==2,430 octets)



Getting To Your Home

- *Local loop* describes connection from telephone office to your home
- Sometimes called *POTS* (Plain Old Telephone Service)
- Legacy infrastructure is copper
  - ISDN, DSL
- Other available connections include
  - Cable TV
  - Wireless
  - Electric power

ISDN

- Integrated Services Digital Network
- Provides digital service (like T-series) on existing local loop copper
- Three separate circuits, or *channels*
  - Two *B* channels, 64 Kbps each; == 2 voice circuits
  - One *D* channel, 16 Kbps; control
- Often written as *2B+D*; called *Basic Rate Interface* (BRI)
- Slow to catch on
  - Expensive
  - Charged by time used like POTS
  - (Almost) equaled by analog modems
  - Was required for some video conferencing apps

DSL

- *DSL* (Digital Subscriber Line) is a family of technologies
  - Sometimes called *xDSL*
  - Provides high-speed digital service over existing local loop
- One common form is *ADSL* (Asymmetric DSL)
  - Higher speed into home than out of home
  - More bits flow in ("downstream") than out ("upstream")
- ADSL maximum speeds:
  - 6.144 Mbps downstream
  - 640 Kbps upstream

Adaptive Transmission

- Individual local loops have different transmission characteristics
  - Different maximum frequencies
  - Different interference frequencies
- ADSL uses FDM
  - 286 frequencies or channels, each 4Khz bandwidth
    - 255 downstream
    - 31 upstream
    - 2 control
- Each frequency carries data independently
  - All frequencies out of audio range
  - Bit rate adapts to quality in each frequency

Other DSL's

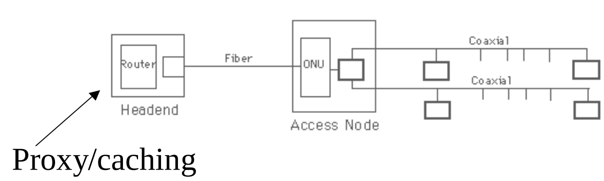
- *SDSL* (Symmetric DSL) provides divides frequencies evenly
- *HDSL* (High-rate DSL) provides DS1 bit rate both directions
  - Short distances
  - Four wires
- *VDSL*(Very high bit rate DSL) provides up to 52 Mbps
  - Very short distance
  - Requires *Optical Network Unit* (ONU) as a relay

Cable Modems

- Cable TV already brings high bandwidth coax into your house
- *Cable modems* encode and decode data from cable TV coax
  - One in cable TV center connects to network
  - One in home connects to computer
- Bandwidth multiplexed among all users over tree-based topology
- Multiple access medium; your neighbor can see your data!
- Not all cable TV coax plants are bidirectional, makes upstream more difficult
  - Originally only had amplifiers for downstream

Hybrid Fiber Coax

- HFC used to provide efficient two-way communications
  - Combination of optical fibers and coax, with fiber for central facilities and coax to the individuals
  - Requires upgrade to network, replace feeder networks with fiber to the trunk with fiber
  - Time division multiplexing
  - 50-450 Mhz for TV, 6Mhz per TV channel
  - 450-750 Mhz for downstream data
  - 5-50 Mhz for upstream data



Summary

- WAN links between sites use digital telephony
  - Based on digitized voice service
  - Several standard rates
  - Requires conversion vis DSU/CSU
- Local loop technologies
  - ISDN
  - xDSL
  - Cable modem
  - Satellite (already discussed previously)
  - Fiber to the curb (fiber boon seems to be ending now, so not too likely)

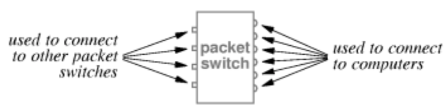
WAN Technologies / Routing

- Here we'll look at WAN technologies and an overview of how routing works in general
- We'll see specific details on implementations of routing later

- Recall
  - LANs to MANs to WANs
  - Need different technology to implement WANs then we have for LANs
  - WAN must be scalable to long distances and many systems

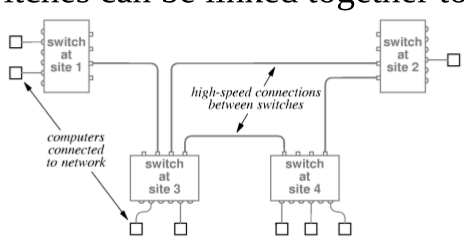
Packet Switches

- To span long distances or many computers, network must replace *shared medium* with *packet switches*
  - Each switch moves an *entire packet* from one connection to another
  - A small computer with network interfaces, memory and program dedicated to packet switching function
  - Packets switches may connect to computers and to other packet switches
  - Typically high speed connections to other packets switches, lower speed to computers
  - Technology details depend on desired speed



Switches as Building Blocks

- Packet switches can be linked together to form WANs



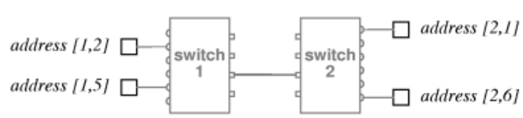
- WANs need not be symmetric or have regular connections
- Each switch may connect to one or more other switches and one or more computers

Store & Forward Switches

- Switches commonly use *Store & Forward*
  - Packet switch *stores* incoming packet
  - ... and *forwards* the packet to another switch or computer
- Packet switch has internal memory
  - Can hold packet if outgoing connection is busy
  - Packets for each connection held on queue
  - This also lets us do things like error detection if we like, and discard bad packets, unlike cut-through switches which only examine the headers and then forward the rest of the packet on

Physical Addressing in a WAN

- Similar to LAN
  - Data transmitted in *packets* (equivalent to frames)
  - Each packet has format with header
  - Packet header includes destination and source addresses
- Many WANs use *hierarchical addressing* for efficiency
  - One part of address identifies destination switch
  - Other part of address identifies port on switch

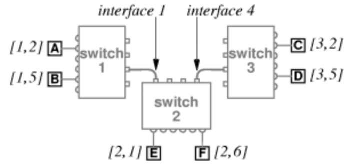


Next Hop Forwarding

- Packet switch must choose outgoing connection for forwarding
  - If destination is local computer, packet switch delivers computer port
  - If destination is attached another switch, this packet switch forwards to *next hop* through connection to another switch
- Choice based on destination address in packet

Next Hop Example

- Packet switch doesn't keep complete information about all possible destination
  - Just keeps next hop
  - So, for each packet, packet switch looks up destination in table and forwards through connection to next hop
- Example for Switch 2



(a)

destination	next hop
[1,2]	interface 1
[1,5]	interface 1
[3,2]	interface 4
[3,5]	interface 4
[2,1]	computer E
[2,6]	computer F

(b)

Source Independence

- Next hop to destination does not depend on source of packet
- Called *source independence*
- Allows fast, efficient routing
- Packet switch need not have complete information, just next hop
  - Reduces total information
  - Increases dynamic robustness - network can continue to function even if topology changes *without* notifying entire network

Routing

- Process of forwarding is called *routing*
- Information is kept in *routing table*
- Note that many entries have same next hop
- In particular, all destinations on same switch have same next hop
- Thus, routing table can be collapsed:

Destination	Next Hop
(1, anything)	interface 1
(3, anything)	interface 4
(2, anything)	local computer

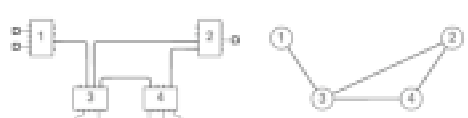
WAN Routing

- More computers == more traffic
- Can add capacity to WAN by adding more links and packet switches
- Packet switches need not have computers attached
- *Interior switch* - no attached computers
- *Exterior switch* - attached computers

- Note: Interior and Exterior will have different meanings when we talk about routing across different networks; (interior == in our network, exterior == connected to outside network)

WAN Routing

- Both interior and exterior switches:
  - Forward packets
  - Need routing tables
- Must have:
  - *Universal routing* - next hop for each possible destination
  - *Optimal routes* - next hop in table must be on shortest path to destination
- Use a graph to model
  - Nodes model switches
  - Edges model direct connections between switches
  - Captures essence of network, ignoring attached computers



Routing Theory

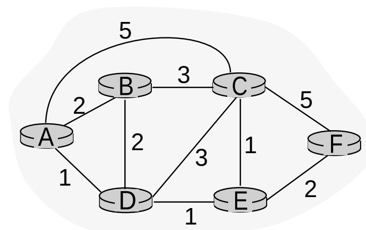
Goal: determine "good" path (sequence of routers) thru network from source to dest.

Graph abstraction for routing algorithms:

⌘ graph nodes are routers

⌘ graph edges are physical links

- link cost: delay, $ cost, hops, or congestion level



Least cost path from A to C?

- "good" path:
  - typically means minimum cost path
  - other def's possible

Route Computation via Graph

- Can represent previous routing table with edges:

destin-ation	next hop
1	-
2	(1,3)
3	(1,3)
4	(1,3)

node 1

destin-ation	next hop
1	(2,3)
2	-
3	(2,3)
4	(2,4)

node 2

destin-ation	next hop
1	(3,1)
2	(3,2)
3	-
4	(3,4)

node 3

destin-ation	next hop
1	(4,3)
2	(4,2)
3	(4,3)
4	-

node 4

- Graph algorithms can be applied to find routes

Redundant Routing Info

- Notice duplication of information in routing table for node 1:

destin-ation	next hop
1	-
2	(1,3)
3	(1,3)
4	(1,3)

node 1

destin-ation	next hop
1	(2,3)
2	-
3	(2,3)
4	(2,4)

node 2

destin-ation	next hop
1	(3,1)
2	(3,2)
3	-
4	(3,4)

node 3

destin-ation	next hop
1	(4,3)
2	(4,2)
3	(4,3)
4	-

node 4

- Switch 1 has only one outgoing connection; all traffic must traverse that connection
- Can collapse routing table entries with a *default route*
- If destination does not have an explicit routing table entry, use use the default route, specified by *

destin-ation	next hop
1	-
*	(1,3)

node 1

destin-ation	next hop
2	-
4	(2,4)
*	(2,3)

node 2

destin-ation	next hop
1	(3,1)
2	(3,2)
3	-
4	(3,4)

node 3

destin-ation	next hop
2	(4,2)
4	-
*	(4,3)

node 4

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

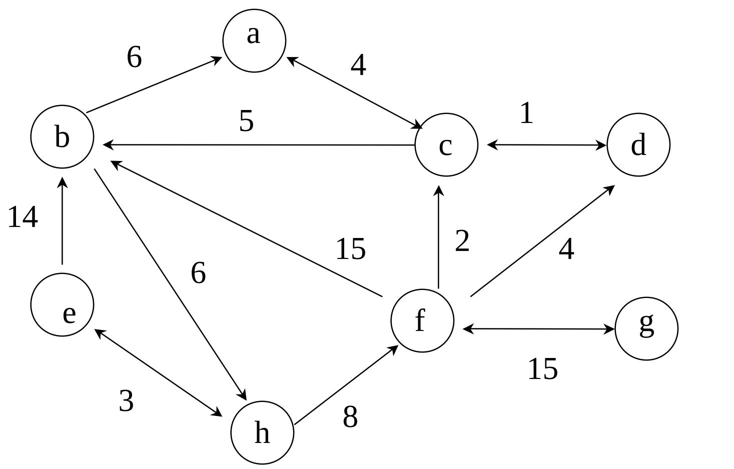
Dijkstra's algorithm

- 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 dest.'s

Dijkstra's Algorithm

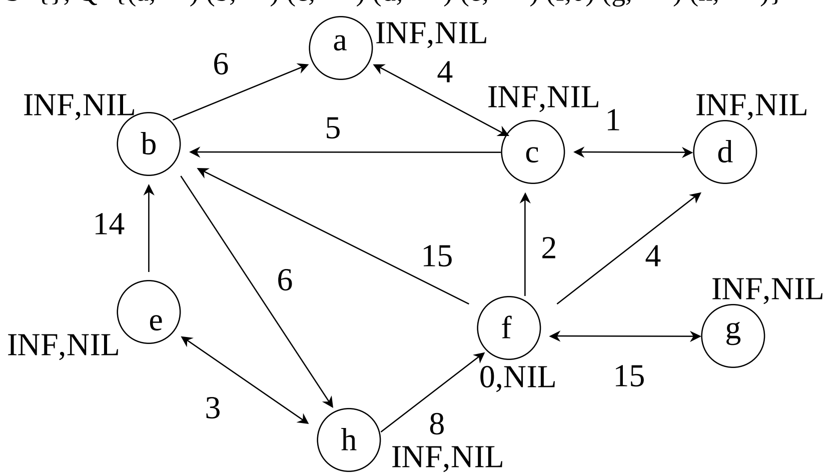
```
Dijkstra(G,w,s)              ; Graph G, weights w, source s
        for each vertex v∈ G, set d[v] ← ∞ and P[v] ← NIL
        d[s] ← 0
        S ← {}
        Q ← All Vertices in G with associated d
        while Q not empty do
                u ← Extract-Min(Q)
                S ← S∪ {u}
                for each vertex v ∈ Adj[u] do
                        if d[v]>d[u]+w(u,v) then
                                d[v] ← d[u]+w(u,v)  ; decrement distance
                                P[v] ← u            ; indicate parent node
```

Dijkstra Example (0)



Dijkstra Example 1

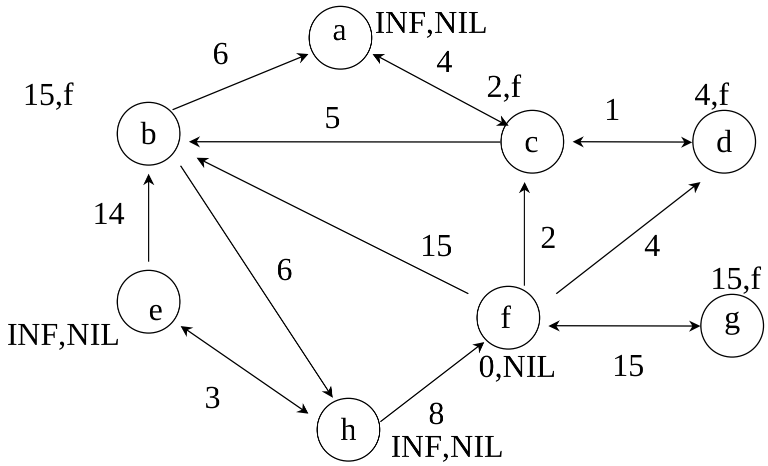
Initialize nodes to ∞ , parent to nil.
S={}, Q={(a,∞) (b,∞) (c, ∞) (d, ∞) (e, ∞) (f,0) (g, ∞) (h, ∞)}



Extract min, vertex f. S={f}. Update shorter paths.

Dijkstra Example 2

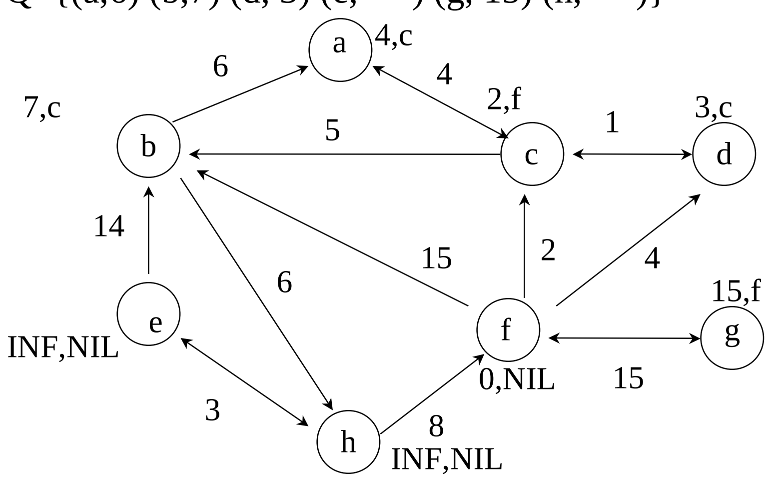
Q={(a, ∞) (b,15) (c, 2) (d, 4) (e, ∞) (g, 15) (h, ∞)}



Extract min, vertex c. S={fc}. Update shorter paths.

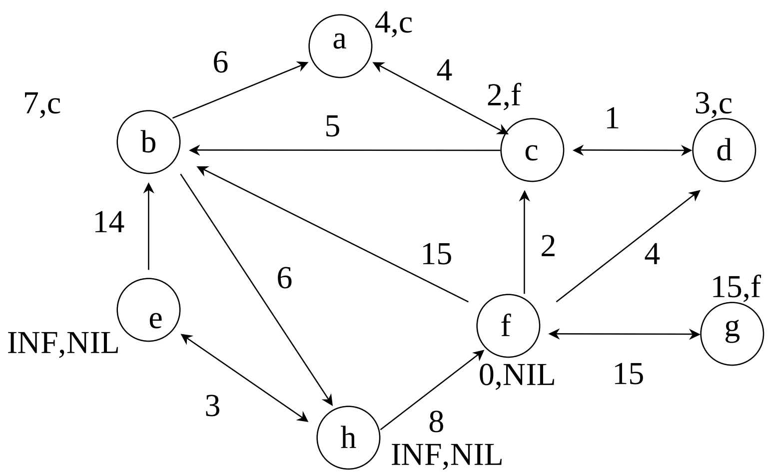
Dijkstra Example 3

Q={(a,6) (b,7) (d, 3) (e, ∞) (g, 15) (h, ∞)}



Extract min, vertex d. S={fcd}. Update shorter paths (None)

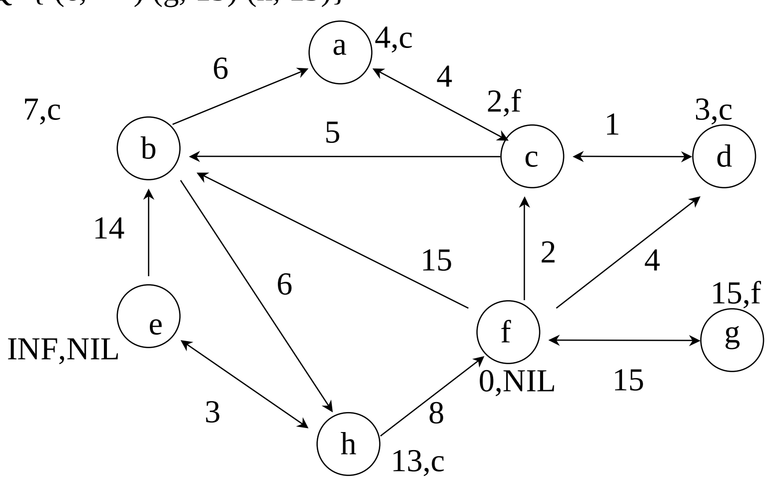
Dijkstra Example 4



Extract min, vertex a. S={fcda}. Update shorter paths (None)
Extract min, vertex b. S={fcdab}. Update shorter paths.

Dijkstra Example 5

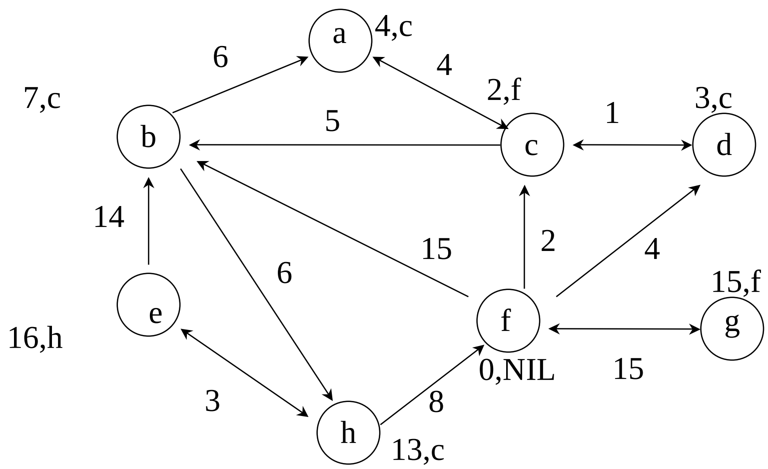
Q={ (e, ∞) (g, 15) (h, 13)}



Extract min, vertex h. S={fcdabh}. Update shorter paths

Dijkstra Example 6

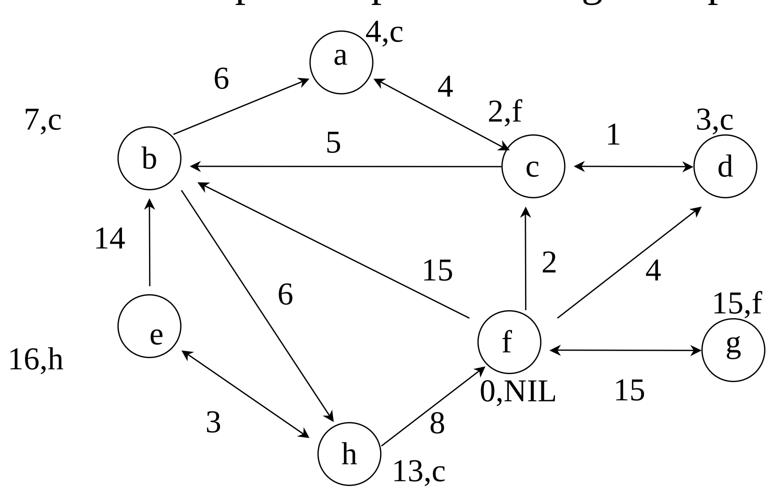
Q={ ((e, 16) (g, 15) }



Extract min, vertex g and h – nothing to update, done!

Dijkstra Example 7

- Can follow parent "pointers" to get the path



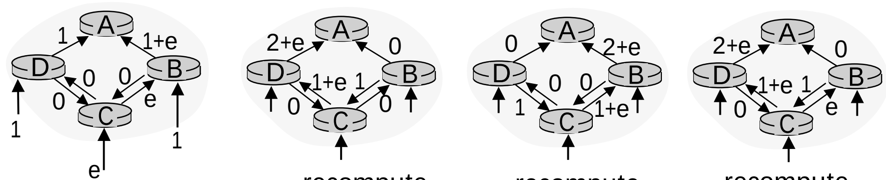
Dijkstra's algorithm, discussion

Algorithm complexity: n nodes

- each iteration: need to check all nodes
- n*(n+1)/2 comparisons: $O(n^2)$ - using linear array for Q
- more efficient implementations possible: O(nlgn) – using min heap for Q

Oscillations possible for some pathological cases:

- e.g., link cost = amount of carried traffic
- Possible solutions?



Initially ctr-clockwise | ... recompute routing clockwise | ... recompute ctr-clockwise | ... recompute clockwise

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

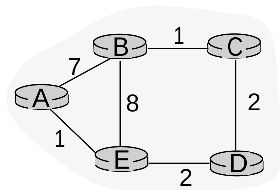
Distance Table data structure

- 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

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

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

$D^E()$ (destination)	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

Distance table gives routing table

cost to destination via

$D^E()$ (destination)	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

destination	Outgoing link to use, cost
A	A,1
B	D,5
C	D,4
D	D,2

Distance table $\longrightarrow$ Routing 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:

wait for (change in local link cost of msg from neighbor)

recompute distance table

if least cost path to any dest has changed, *notify* neighbors

Distance Vector Algorithm:

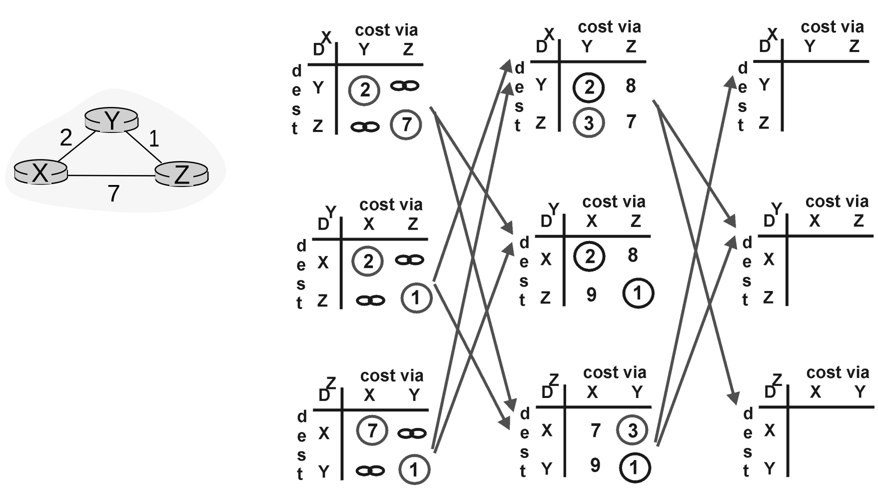
At all nodes, X:

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

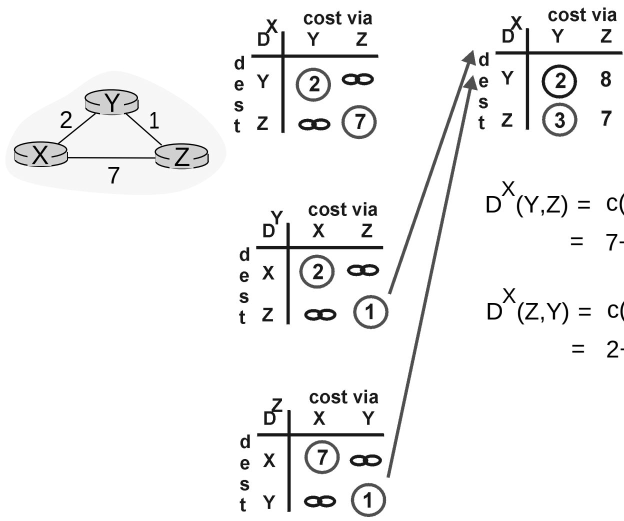
Distance Vector Algorithm (cont.):

```
loop
  wait (until I see a link cost change to neighbor V
        or until I receive update from neighbor V)

  if (c(X,V) changes by d)
    /* change cost to all dest's via neighbor v by d */
    /* note: d could be positive or negative */
    for all destinations y:  D^X(y,V) =  D^X(y,V) + d

  else if (update received from V wrt destination Y)
    /* shortest path from V to some Y has changed  */
    /* V has sent a new value for its  min_w D^V(Y,w) */
    /* call this received new value is "newval"     */
    for the single destination y: D^X(Y,V) = c(X,V) + newval

  if we have a new min_w D^X(Y,w)for any destination Y
     send new value of min_w D^X(Y,w) to all neighbors

forever
```

Distance Vector Algorithm: example



Distance Vector Algorithm: example



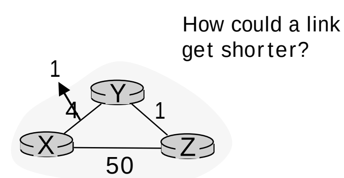
$$D^X(Y,Z) = c(X,Z) + \min_w\{D^Z(Y,w)\}$$
$$= 7+1 = 8$$

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

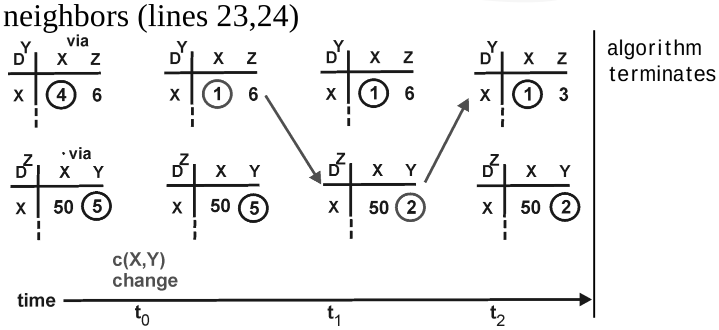
Distance Vector: link cost changes

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)



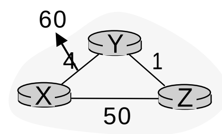
"good news travels fast"

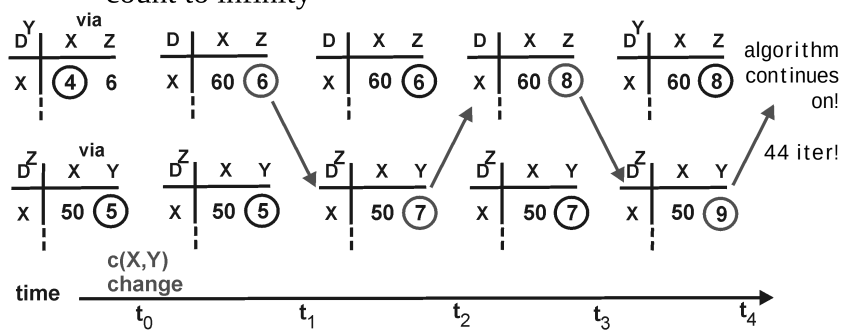


Distance Vector: link cost changes

Link cost changes:

- good news travels fast
- bad news travels slow - "count to infinity"





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-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
  - Could cause a flood

Routing Implementation

- Link State (Dijkstra’s Algorithm)
  - Used in OSPF
- Distance Vector (Bellman-Ford Algorithm)
  - Used in Internet BGP, IPX, RIP

Examples of WAN Technology

- ARPANET
  - Original precursor to the ‘Net
- X.25
  - Early standard for connection-oriented networking
  - From *ITU*, which was originally *CCITT*
  - Predates computer connections, used for terminal/timesharing connection
- Frame Relay
  - Telco service for delivering blocks of data
  - Connection-based service; must contract with telco for *circuit* between two endpoints
  - Typically 56Kbps or 1.5Mbps; can run to 100Mbps

Examples of WAN Technology

- SMDS - *Switched Multi-megabit Data Service*
  - Also a Telco service
  - Connectionless service; any SMDS station can send a frame to any other station on the same SMDS "cloud"
  - Typically 1.5-100Mbps
- ATM - *Asynchronous Transfer Mode*
  - Designed as single technology for voice, video, data, ...
  - Low *jitter* (variance in delivery time) and high capacity
  - Uses fixed size, small *cells* - 48 octets data, 5 octets header
  - Can connect multiple ATM switches into a network

Summary

- WAN can span arbitrary distances and interconnect arbitrarily many computers
- Uses packet switches and point-to-point connections
- Packets switches use store-and-forward and routing tables to deliver packets to destination
- WANs use hierarchical addressing
- Graph algorithms can be used to compute routing tables
- Many LAN technologies exist