CSC 358 – Principles of Computer Networks

Handout # 5: The Internet Protocol, Routing and Forwarding

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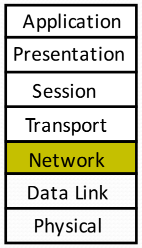
Announcements

- Don't forget the programming assignment.
  - Due: Friday, Feb 16, 2018 at 11:59pm.
  - Take advantage of tutorials.
  - Don't leave it to the last minute.
  - Create your group in MarkUs.
  - Remember, use the autotester script
- Late Penalty
  - 2.5% per 6 hrs

The Story

- So far …
  - Layers, and protocols
  - Link layer
  - Interconnecting LANs
    - Hubs, switches, and bridges
  - The Internet Protocol
    - IP datagram, fragmentation
    - Naming and addressing
    - CIDR, DNS
- This time
  - Routing and forwarding



Packet Routing and Forwarding

ARP, Addressing, A Day in the Life: Scenario

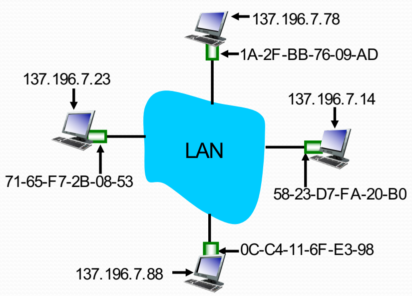
- Forwarding IP datagrams
  - Class-based vs. CIDR
- Routing Techniques
  - Naïve: Flooding
  - Distance vector: Distributed Bellman Ford Algorithm
  - Link state: Dijkstra's Shortest Path First-based Algorithm

ARP: Address Resolution Protocol

Question: how to determine interface's MAC address, knowing its IP address?

ARP table: each IP node (host, router) on LAN has table

- IP/MAC address mappings for some LAN nodes:
  < IP address; MAC address; TTL>
- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)



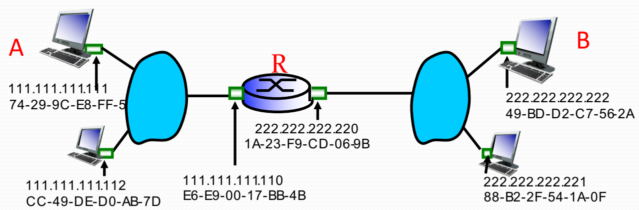
ARP Protocol: Same LAN

- A wants to send datagram to B
  - B's MAC address not in A's ARP table.
- A **broadcasts** ARP query packet, containing B's IP address
  - destination MAC address = FF-FF-FF-FF-FF-FF
  - all nodes on LAN receive ARP query
- B receives ARP packet, replies to A with its (B's) MAC address
  - frame sent to A's MAC address (unicast)
- A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (times out)
  - soft state: information that times out (goes away) unless refreshed
- ARP is "plug-and-play":
  - nodes create their ARP tables *without intervention from net administrator*

Addressing: Routing to another LAN

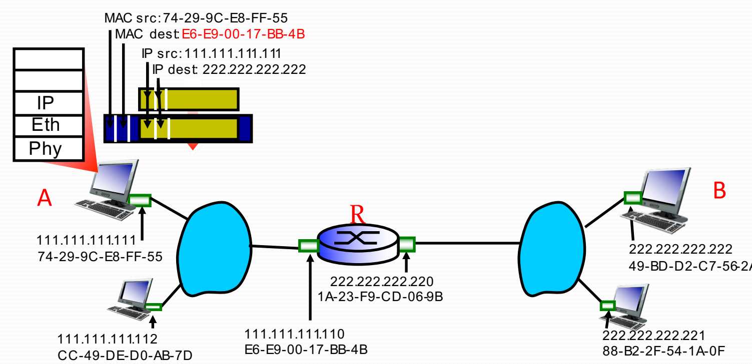
walkthrough: send datagram from A to B via R

- focus on addressing – at IP (datagram) and MAC layer (frame)
- assume A knows B's IP address
- assume A knows IP address of first hop router, R (how?)
- assume A knows R's MAC address (how?)



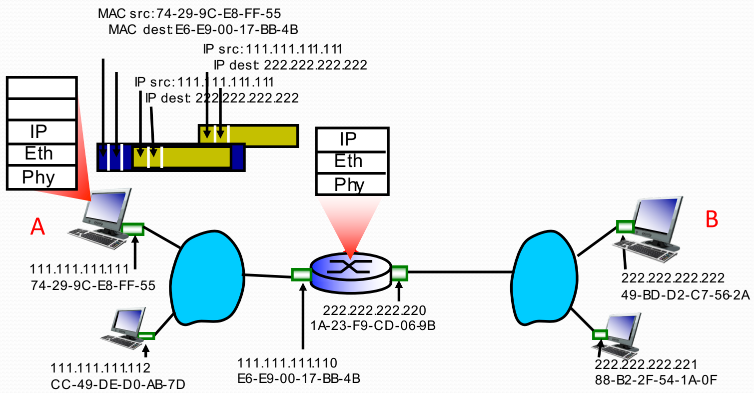
Addressing: Routing to another LAN

- A creates IP datagram with IP source A, destination B
- A creates link-layer frame with R's MAC address as destination address, frame contains A-to-B IP datagram



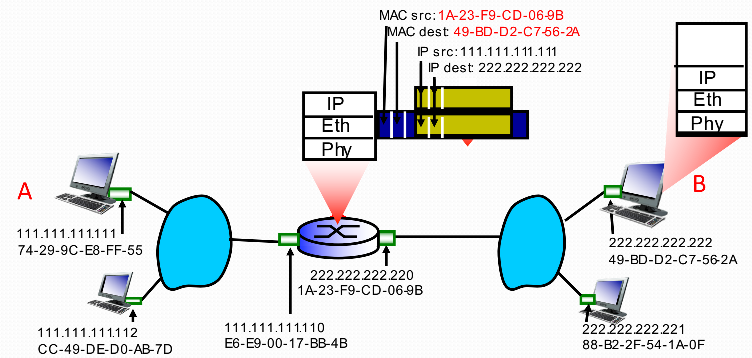
Addressing: Routing to another LAN

- frame sent from A to R
- frame received at R, datagram removed, passed up to IP



Addressing: Routing to another LAN

- R forwards datagram with IP source A, destination B
- R creates link-layer frame with B's MAC address as destination address, frame contains A-to-B IP datagram



Addressing: Routing to another LAN

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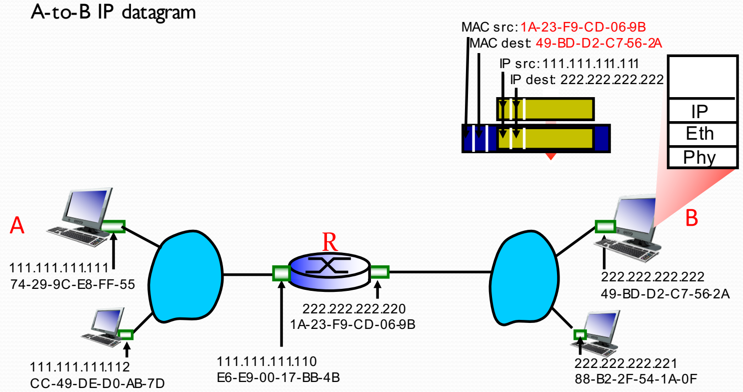
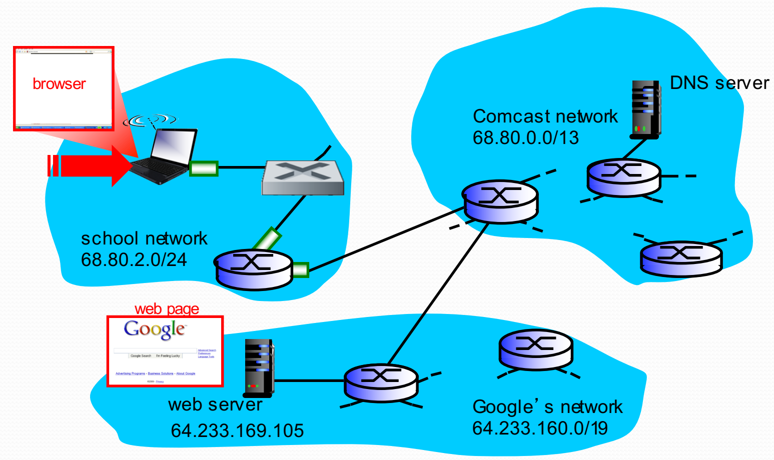
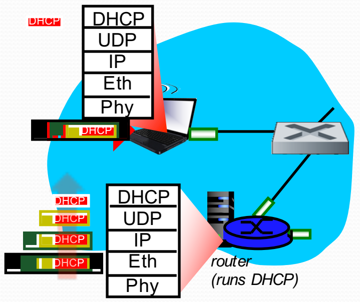


A day in the life: Scenario

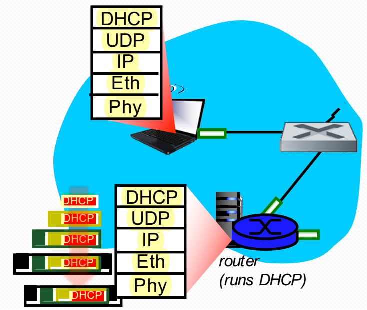


A day in the life… connecting to the Internet



- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use *DHCP*
- DHCP request encapsulated in UDP, encapsulated in IP, encapsulated in 802.3 Ethernet
- Ethernet frame broadcast (dest: FFFFFFFFFFFF) on LAN, received at router running DHCP server

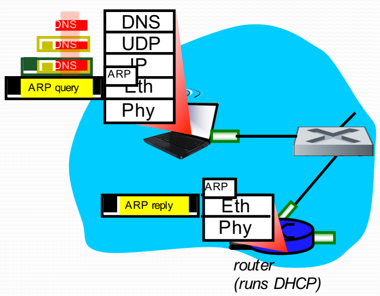
A day in the life… connecting to the Internet



- DHCP server formulates *DHCP ACK* containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation at DHCP server, frame forwarded (switch learning) through LAN, demultiplexing at client
- DHCP client receives DHCP ACK reply

Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

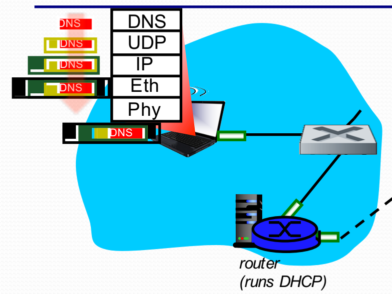
A day in the life… ARP (before DNS, before HTTP)

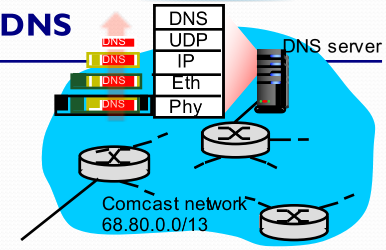


- before sending *HTTP* request, need IP address of www.google.com: *DNS*

- DNS query created, encapsulated in UDP, encapsulated in IP, encapsulated in Eth. To send frame to router, need MAC address of router interface: ARP
- ARP query broadcast, received by router, which replies with ARP reply giving MAC address of router interface
- client now knows MAC address of first hop router, so can now send frame containing DNS query

A day in the life… using DNS

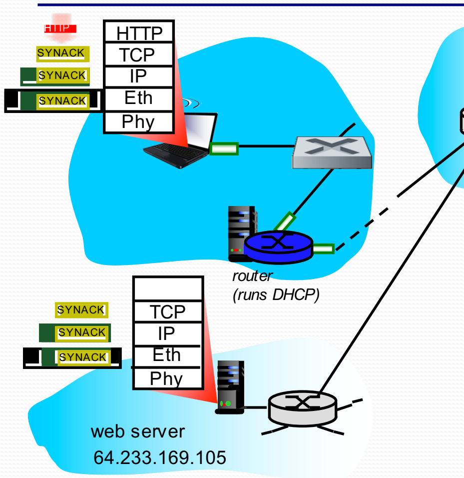




- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router

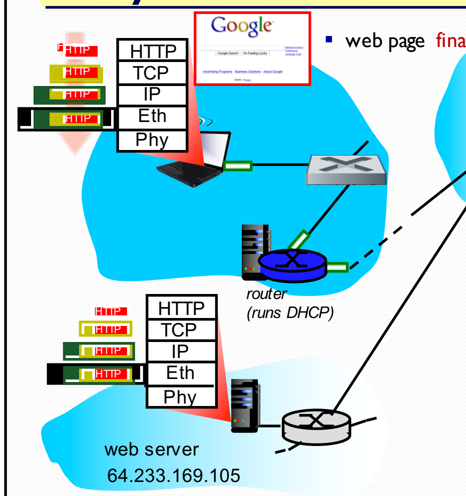
- IP datagram forwarded from campus network into Comcast network, routed (tables created by RIP, OSPF, IS-IS and/or BGP routing protocols) to DNS server
- demuxed to DNS server
- DNS server replies to client with IP address of www.google.com

A day in the life…TCP connection carrying HTTP



- to send HTTP request, client first opens TCP socket to web server
- TCP SYN segment (step 1 in 3-way handshake) inter-domain routed to web server
- web server responds with TCP SYNACK (step 2 in 3-way handshake)
- TCP connection established!

A day in the life… HTTP request/reply



- web page finally (!!!) displayed
- HTTP request sent into TCP socket
- IP datagram containing HTTP request routed to www.google.com
- web server responds with HTTP reply (containing web page)
- IP datagram containing HTTP reply routed back to client

Packet Routing and Forwarding

- ARP, Addressing, A Day in the Life: Scenario

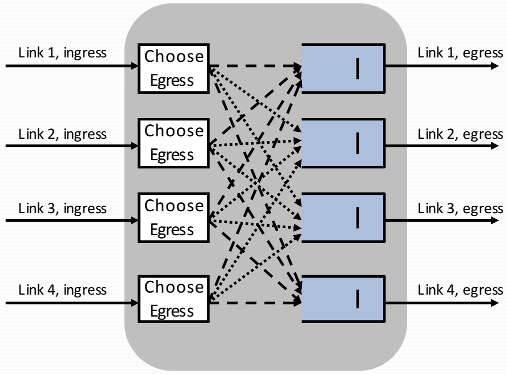
- Forwarding IP datagrams
  - Class-based vs. CIDR

- Routing Techniques
  - Naïve: Flooding
  - Distance vector: Distributed Bellman Ford Algorithm
  - Link state: Dijkstra's Shortest Path First-based Algorithm

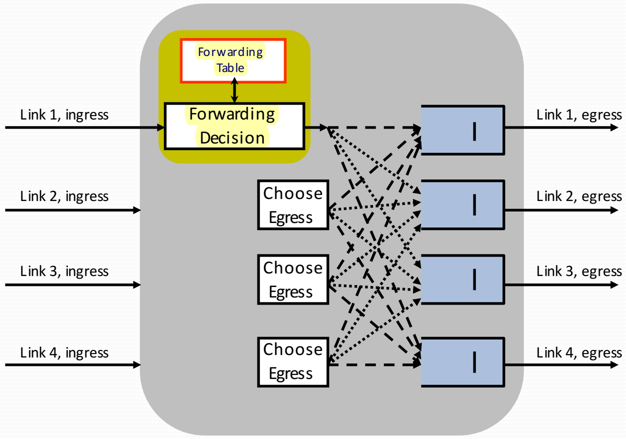
Hop-by-Hop Packet Forwarding

- Each router has a forwarding table
  - Maps destination addresses…
  - … to outgoing interfaces
- Upon receiving a packet
  - Inspect the destination IP address in the header
  - Index into the table
  - Determine the outgoing interface
  - Forward the packet out that interface
- Then, the next router in the path repeats
  - And the packet travels along the path to the destination

Inside a Router



Inside a Router



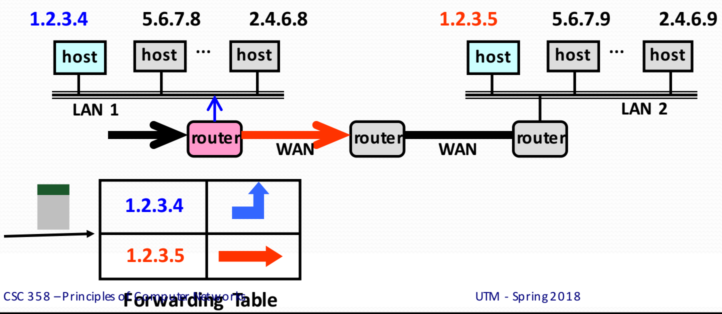
Forwarding in an IP Router

- Lookup packet DA in forwarding table.
  - If known, forward to correct port.
  - If unknown, drop packet.
- Decrement TTL, update header Checksum.
- Forward packet to outgoing interface.
- Transmit packet onto link.

Question: How is the address looked up in a real router?

Separate Table Entries Per Address

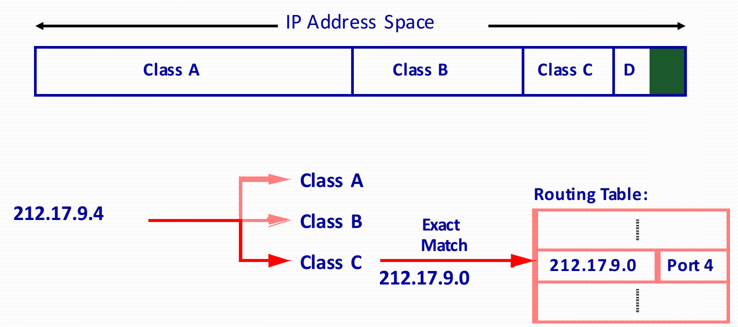
- If a router had a forwarding entry per IP address
  - Match destination address of incoming packet
  - … to the forwarding-table entry
  - … to determine the outgoing interface



Separate Entry Class-based Address

- If the router had an entry per class-based prefix
  - Mixture of Class A, B, and C addresses
  - Depends on the first couple of bits of the destination
- Identify the mask automatically from the address
  - First bit of 0: class A address (/8)
  - First two bits of 10: class B address (/16)
  - First three bits of 110: class C address (/24)
- Then, look in the forwarding table for the match
  - E.g., 1.2.3.4 maps to 1.2.3.0/24
  - Then, look up the entry for 1.2.3.0/24
  - … to identify the outgoing interface

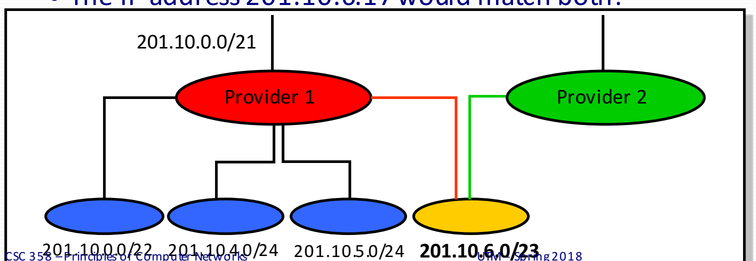
Example – *Class-based Addressing*



Exact Match: There are many well-known ways to find an exact match in a table.

CIDR Makes Packet Forwarding Harder

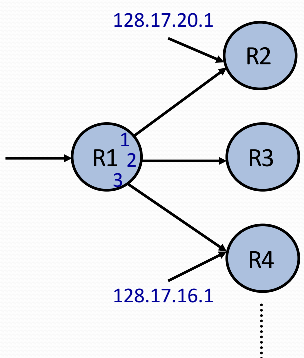
- There's no such thing as a free lunch
  - CIDR allows efficient use of the limited address space
  - But, CIDR makes packet forwarding much harder
- Forwarding table may have many matches
  - E.g., table entries for 201.10.0.0/21 and 201.10.6.0/23
  - The IP address 201.10.6.17 would match both!



Longest Prefix Match Forwarding

- Forwarding tables in IP routers
  - Maps each IP *prefix* to next-hop link(s)
- Destination-based forwarding
  - Packet has a destination address
  - Router identifies longest-matching prefix
  - Cute algorithmic problem: very fast lookups

How a Router Forwards Datagrams



e.g. 128.9.16.14 => Port 2

Prefix	Next-hop	Port
65/8	128.17.16.1	3
128.9/16	128.17.14.1	2
128.9.16/20	128.17.14.1	2
128.9.19/24	128.17.10.1	7
128.9.25/24	128.17.14.1	2
128.9.176/20	128.17.20.1	1
142.12/19	128.17.16.1	3

Forwarding Table

Simplest Algorithm is Too Slow

- Scan the forwarding table one entry at a time
  - See if the destination matches the entry
  - If so, check the size of the mask for the prefix
  - Keep track of the entry with longest-matching prefix
- Overhead is linear in size of the forwarding table
  - Today, that means 400,000-500,000 entries!
  - And, the router may have just a few nanoseconds
  - ... before the next packet is arriving
- Need greater efficiency to keep up with line rate
  - Better algorithms
  - Hardware implementations

Lookup Performance Required

Line	Line Rate	Pktsize=40B	Pktsize=240B
T1	1.5Mbps	4.68 Kpps	0.78 Kpps
OC3	155Mbps	480 Kpps	80 Kpps
OC12	622Mbps	1.94 Mpps	323 Kpps
OC48	2.5Gbps	7.81 Mpps	1.3 Mpps
OC192	10 Gbps	31.25 Mpps	5.21 Mpps

Fast Lookups

- The are algorithms that are faster than linear scan
  - Proportional to number of bits in the address
- We can use special hardware
  - Content Addressable Memories (CAMs)
  - Allows look-ups on a key rather than flat address
- Huge innovations in the mid-to-late 1990s
  - After CIDR was introduced (in 1994)
  - … and longest-prefix match was a major bottleneck

Where do Forwarding Tables Come From?

- Routers have forwarding tables
  - Map prefix to outgoing link(s)
- Entries can be statically configured
  - E.g., "map 12.34.158.0/24 to Serial0/0.1"
- But, this doesn't adapt
  - To failures
  - To new equipment
  - To the need to balance load
  - …
- That is where other technologies come in…
  - Routing protocols, DHCP, and ARP

Packet Routing and Forwarding

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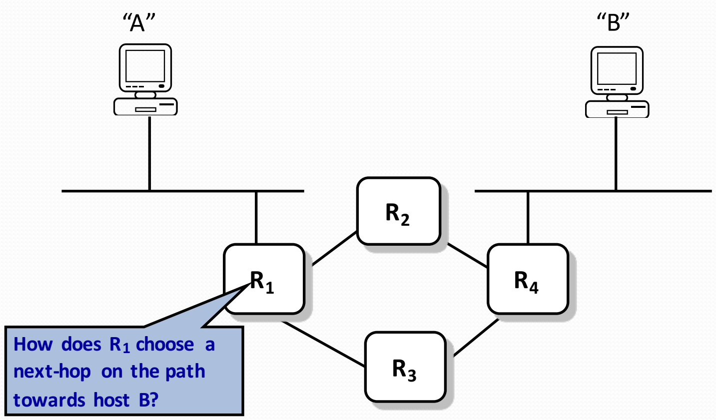
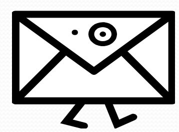
Routing is a very complex subject, and has many aspects. Here, we will concentrate on the basics.

The Problem



What is Routing?

- A famous quotation from RFC 791
  - "A name indicates what we seek.
    An address indicates where it is.
    A route indicates how we get there."
    -- Jon Postel



Forwarding vs. Routing

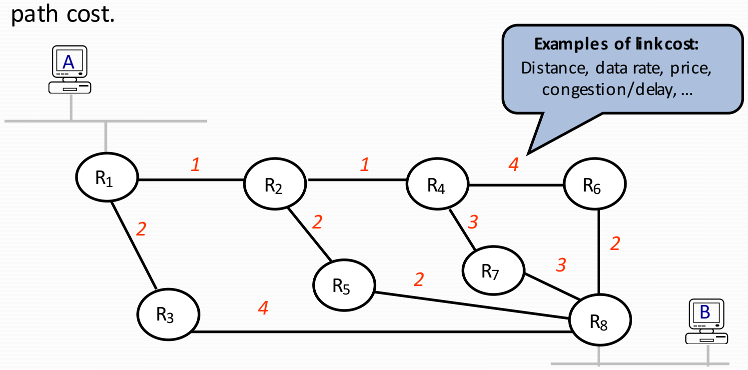
- Forwarding: *data plane*
  - Directing a data packet to an outgoing link
  - Individual router using a forwarding table
- Routing: *control plane*
  - Computing paths the packets will follow
  - Routers talking amongst themselves
  - Individual router creating a forwarding table

Why Does Routing Matter?

- End-to-end performance
  - Quality of the path affects user performance
  - Propagation delay, throughput, and packet loss
- Use of network resources
  - Balance of the traffic over the routers and links
  - Avoiding congestion by directing traffic to lightly-loaded links
- Transient disruptions during changes
  - Failures, maintenance, and load balancing
  - Limiting packet loss and delay during changes

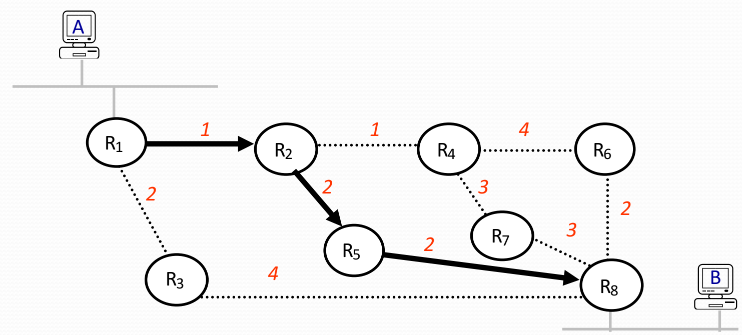
Example Network

Objective: Determine the route from A to B that minimizes the path cost.



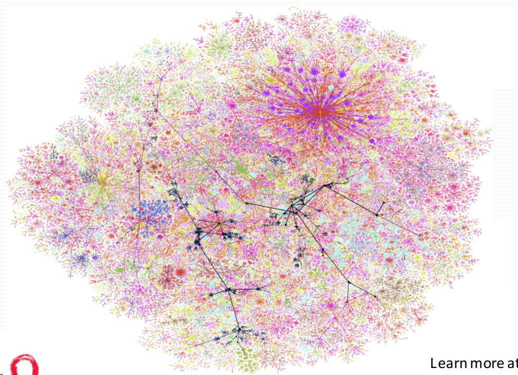
Example Network

In this simple case, solution is clear from inspection



What about this Network…!?

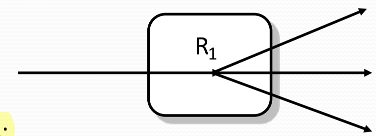
The public Internet in 1999



Learn more at http://www.lumeta.com

Technique 1: Naïve Approach

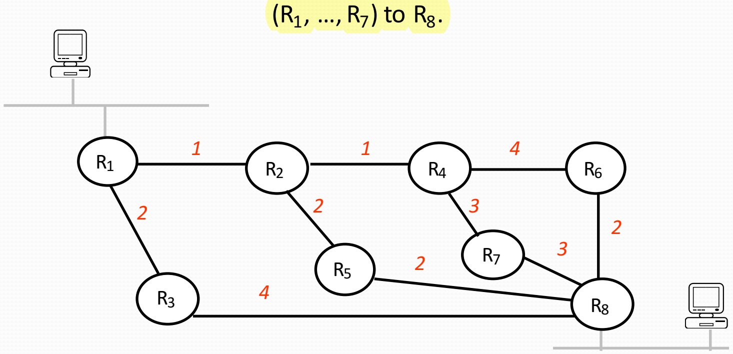
Flood! -- Routers forward packets to all ports except the ingress port.



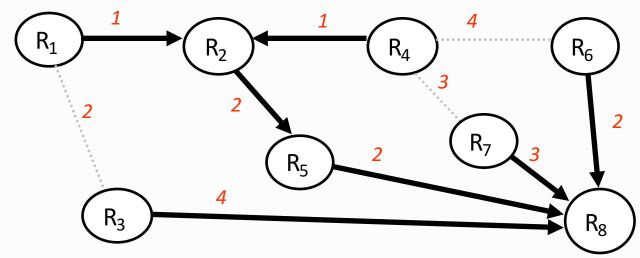
- Advantages:
  - Simple
  - Every destination in the network is reachable.
- Disadvantages:
  - Some routers receive a packet multiple times.
  - Packets can go round in loops forever.
  - Inefficient.

Lowest Cost Routes

Objective: Find the lowest cost route from each of (R_1, …, R_7) to R_8.



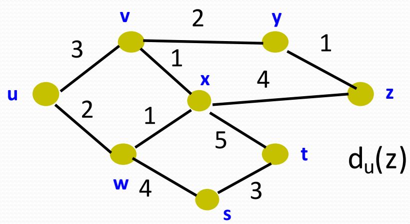
A Spanning Tree



- The solution is a spanning tree with R8 as the root of the tree.
- Tree: There are no loops.
- Spanning: All nodes included.
- We'll see two algorithms that build spanning trees automatically:
  - The distributed Bellman-Ford algorithm
  - Dijkstra's shortest path first algorithm

Technique 2: Distance Vector: Distributed Bellman-Ford Algorithm

- Define distances at each node x
  - $d_x(y)$ = cost of least-cost path from x to y
- Update distances based on neighbors
  - $d_x(y) = \min \{c(x,v) + d_v(y)\}$ over all neighbors v



$$d_u(z) = \min\{c(u,v) + d_v(z), \; c(u,w) + d_w(z)\}$$

Distance Vector Algorithm

- c(x,v) = cost for direct link from x to v
  - Node x maintains costs of direct links c(x,v)
- $D_x(y)$ = estimate of least cost from x to y
  - Node x maintains distance vector $\mathbf{D_x} = [D_x(y): y \in N]$
- Node x maintains its neighbors' distance vectors
  - For each neighbor v, x maintains $\mathbf{D_v} = [D_v(y): y \in N]$
- Each node v periodically sends D_v to its neighbors
  - And neighbors update their own distance vectors
  - $D_x(y) \leftarrow \min_v\{c(x,v) + D_v(y)\}$ for each node $y \in N$
- Over time, the distance vector D_x converges

Distance Vector Algorithm

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

Each node:

wait for (change in local link cost or message from neighbor)

recompute estimates

if DV to any destination has changed, *notify* neighbors

Distance Vector Example: Step 1

Optimum 1-hop paths

Table for A			Table for B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	□	–	C	□	–
D	□	–	D	3	D
E	2	E	E	□	–
F	6	F	F	1	F

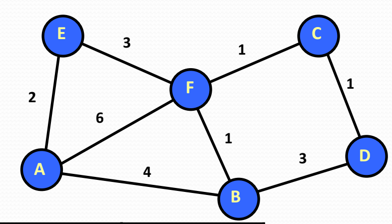


Table for C			Table for D			Table for E			Table for F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	□	–	A	□	–	A	2	A	A	6	A
B	□	–	B	3	B	B	□	–	B	1	B
C	0	C	C	1	C	C	□	–	C	1	C
D	1	D	D	0	D	D	□	–	D	□	–
E	□	–	E	□	–	E	0	E	E	3	E
F	1	F	F	□	–	F	3	F	F	0	F

Distance Vector Example: Step 2

Optimum 2-hop paths

Table for A			Table for B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	7	F	C	2	F
D	7	B	D	3	D
E	2	E	E	4	F
F	5	E	F	1	F

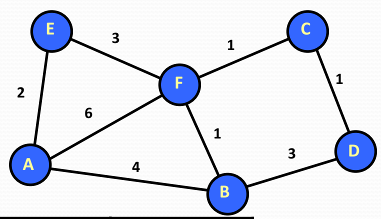


Table for C			Table for D			Table for E			Table for F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	7	F	A	7	B	A	2	A	A	5	B
B	2	F	B	3	B	B	4	F	B	1	B
C	0	C	C	1	C	C	4	F	C	1	C
D	1	D	D	0	D	D	□	–	D	2	C
E	4	F	E	□	–	E	0	E	E	3	E
F	1	F	F	2	C	F	3	F	F	0	F

Distance Vector Example: Step 3

Optimum 3-hop paths

Table for A			Table for B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	6	E	C	2	F
D	7	B	D	3	D
E	2	E	E	4	F
F	5	E	F	1	F

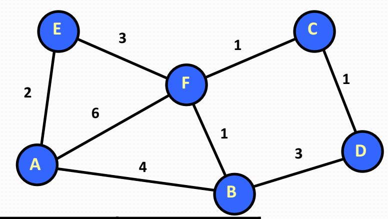


Table for C			Table for D			Table for E			Table for F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	6	F	A	7	B	A	2	A	A	5	B
B	2	F	B	3	B	B	4	F	B	1	B
C	0	C	C	1	C	C	4	F	C	1	C
D	1	D	D	0	D	D	5	F	D	2	C
E	4	F	E	5	C	E	0	E	E	3	E
F	1	F	F	2	C	F	3	F	F	0	F

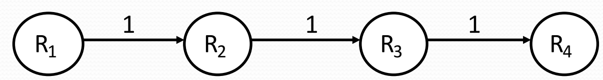
Bellman-Ford Algorithm

- Questions:
  - How long can the algorithm take to run?
  - How do we know that the algorithm always converges?
  - What happens when link costs change, or when routers/links fail?

- Topology changes make life hard for the Bellman-Ford algorithm…

A Problem with Bellman-Ford

Bad news travels slowly



Consider the calculation of distances to R_4:

Time	R_1	R_2	R_3
0	3,R_2	2,R_3	1, R_4
1	3,R_2	2,R_3	3,R_2
2	3,R_2	4,R_3	3,R_2
3	5,R_2	4,R_3	5,R_2
…	"Counting to infinity"		…

$R_3 \longrightarrow R_4$ fails

Counting to Infinity Problem – Solutions

- Set infinity = "some small integer" (e.g. 16). Stop when count = 16.
- Split Horizon: Because R_2 received lowest cost path from R_3, it does not advertise cost to R_3
- Split-horizon with poison reverse: R_2 advertises infinity to R_3
- There are many problems with (and fixes for) the Bellman-Ford algorithm.

Technique 3: Link State

Dijkstra's Shortest Path First Algorithm

- Routers send out update messages whenever the state of an incident link changes.
  - Called "Link State Updates"
- Based on all link state updates received each router calculates lowest cost path to all others, starting from itself.
  - Use Dijkstra's single-source shortest path algorithm
  - Assume all updates are consistent
- At each step of the algorithm, router adds the next shortest (i.e. lowest-cost) path to the tree.
- Finds spanning tree rooted at the router.

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

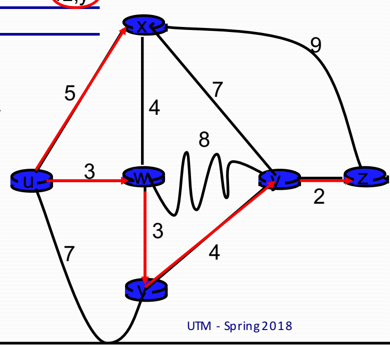
```
Initialization:
  S = {u}
  for all nodes v
    if v adjacent to u {
        D(v) = c(u,v)
    else D(v) = ∞

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)}
until all nodes in S
```

Dijkstra's algorithm: Example

Step	N'					
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					

notes:

- construct shortest path tree by tracing predecessor nodes
- ties can exist (can be broken arbitrarily)

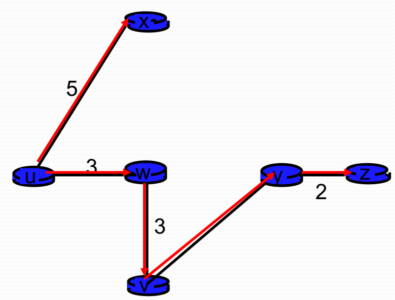


Shortest-Path Tree

resulting forwarding table in u:

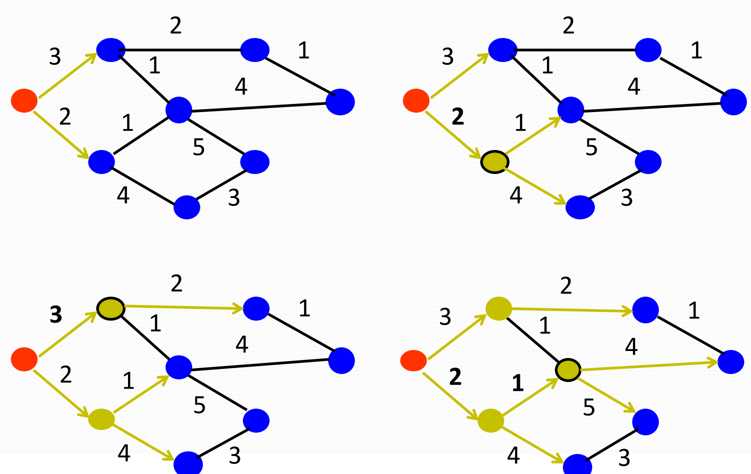
destination	link
v	(u,w)
x	(u,x)
y	(u,w)
w	(u,w)
z	(u,w)

resulting shortest-path tree from u:

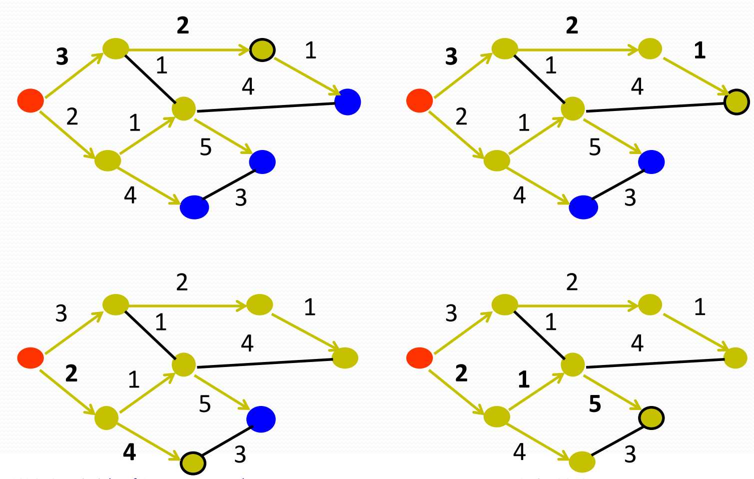


Dijkstra's Algorithm Example

Find Routes for the Red (Leftmost) Node

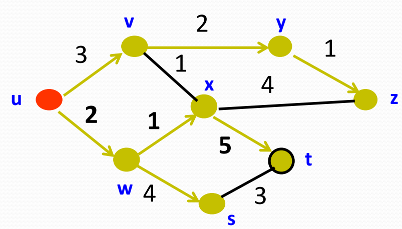


Dijkstra's Algorithm Example



Shortest-Path Tree

Shortest-path tree from u



Forwarding table at u

	link
v	(u,v)
w	(u,w)
x	(u,w)
y	(u,v)
z	(u,v)
s	(u,w)
t	(u,w)

Reliable Flooding of LSP

- The Link State Packet:
  - The ID of the router that created the LSP
  - List of directly connected neighbors, and cost
  - Sequence number
  - TTL
- Reliable Flooding
  - Resend LSP over all links other than incident link, if the sequence number is newer. Otherwise drop it.
- Link State Detection:
  - Link layer failure
  - Loss of “hello” packets

Comparison of LS and DV algorithms

Message complexity

LS: with n nodes, E links, O(nE) messages sent

DV: exchange between neighbors only

- Convergence time varies

Speed of Convergence

LS: $O(n^2)$ algorithm requires O(nE) messages

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 propagates)

Questions?