CSCE 463/612 Networks and Distributed Processing Spring 2025

Network Layer V

Dmitri Loguinov
Texas A&M University

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Chapter 4: Roadmap

4.1 Introduction

4.2 Virtual circuit and datagram networks

4.3 What's inside a router

4.4 IP: Internet Protocol

4.5 Routing algorithms

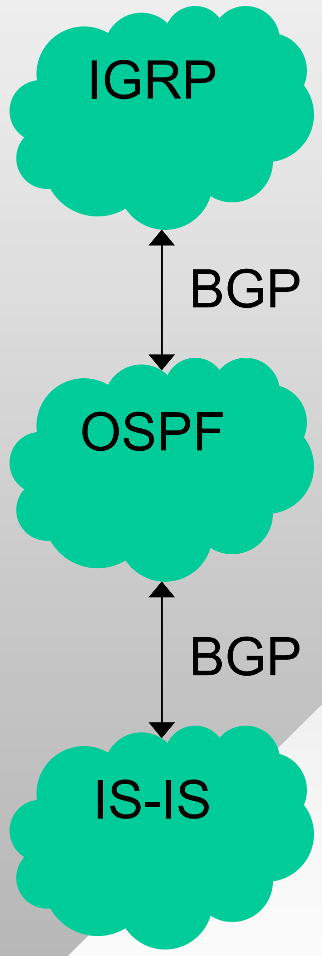
4.6 Routing in the Internet

- RIP
- OSPF
- BGP

4.7 Broadcast and multicast routing

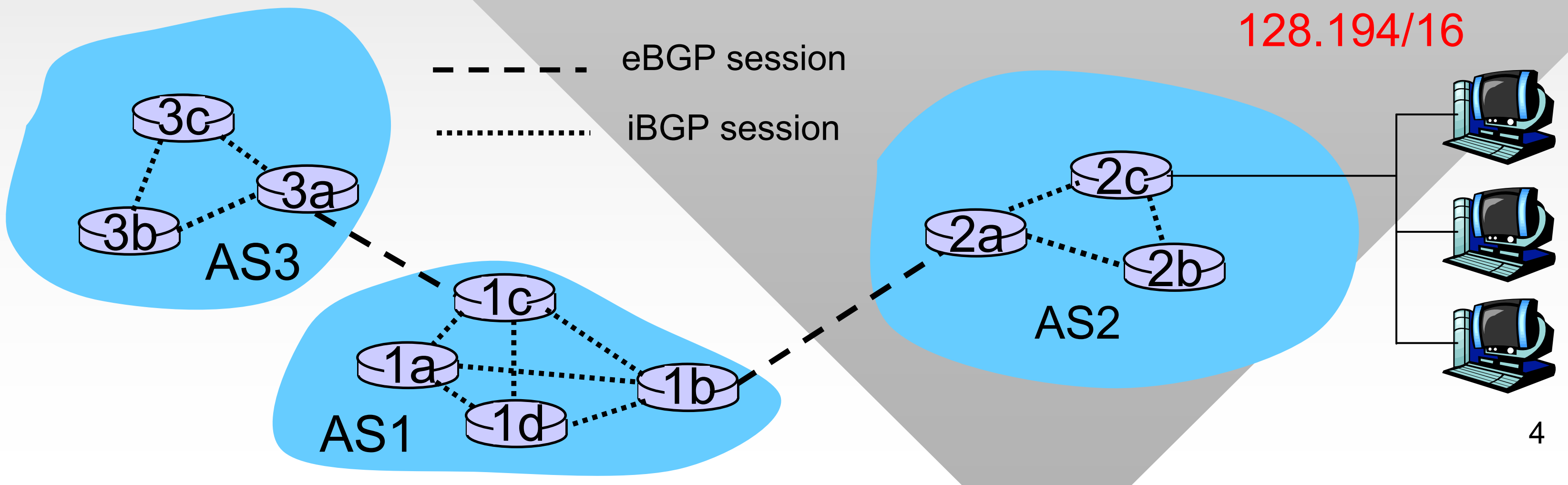
Inter-AS Routing: BGP

- BGP (Border Gateway Protocol): de facto standard for inter-AS (exterior) routing
- BGP provides each AS a means to:
  - Obtain subnet reachability information from neighboring ASes
  - Propagate the reachability information to all routers internal to the AS
  - Determine “good” routes to subnets based on reachability information and policy
- Allows a subnet to advertise its existence to the rest of the Internet: *“I am here”*



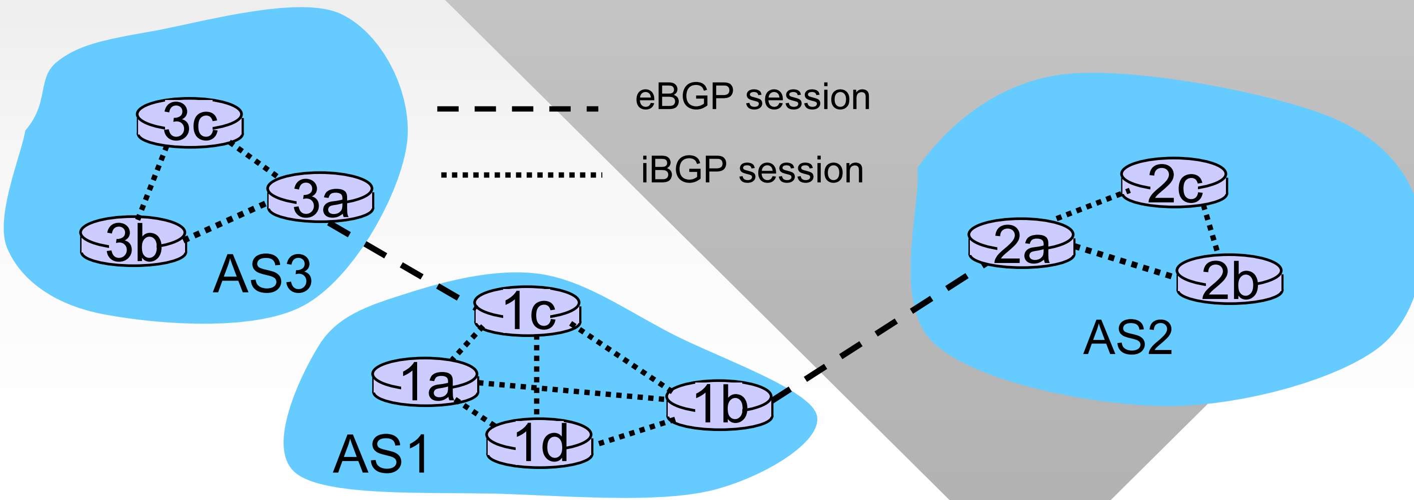
BGP Basics

- Pairs of routers (BGP peers) exchange routing info over TCP connections: BGP sessions
  - Peers do not have to be physically attached to each other
- When AS2 advertises a prefix 128.194/16 to AS1, AS2 is *promising* it will forward any datagrams destined to that prefix towards the prefix
  - AS2 can aggregate prefixes in its advertisement



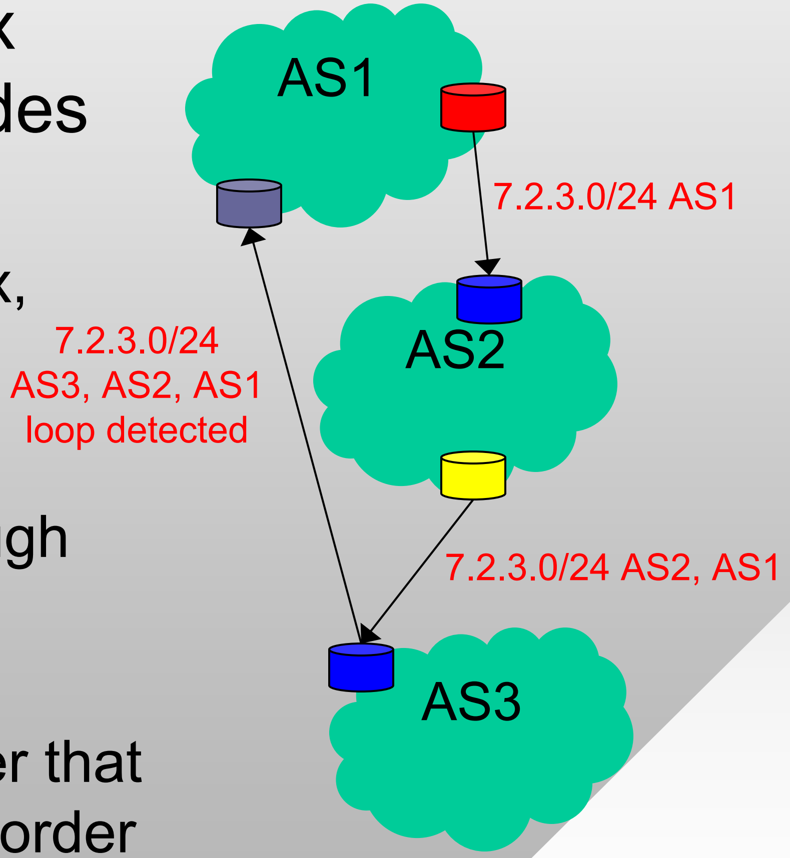
Distributing Reachability Info

- With eBGP session between 2a and 1b, AS2 sends prefix reachability info to AS1
  - 1b can then use iBGP do distribute this to all routers in AS1
  - 1c may (if beneficial to AS1) re-advertise these subnets to AS2 over the 1c-3a eBGP session
- Internal AS routers combine intra-AS data with iBGP broadcasts to set up actual forwarding tables



Path Attributes & BGP Routes

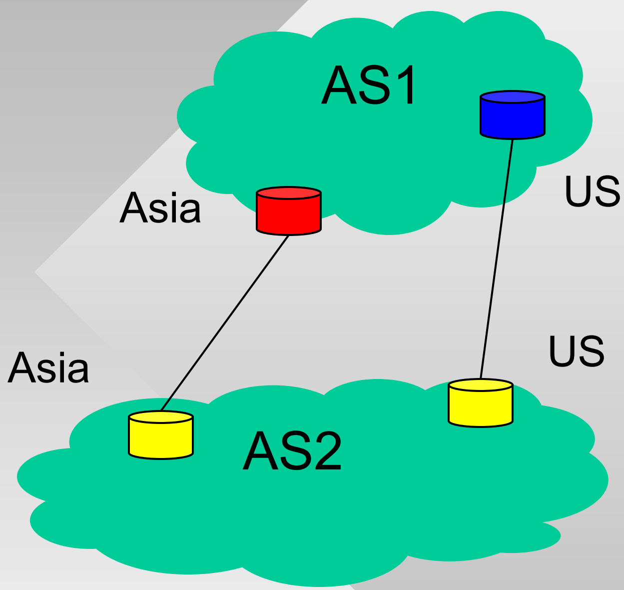
- When advertising an IP prefix (i.e., subnet), message includes BGP attributes
  - Notation: combination (IP prefix, attributes) = route
- Two important attributes:
  - AS-PATH: contains ASes through which the advert for the prefix passed (latest AS first)
  - NEXT-HOP: indicates the router that should receive traffic (usually border router of the AS that advertised prefix; multiple values possible)



BGP Route Selection

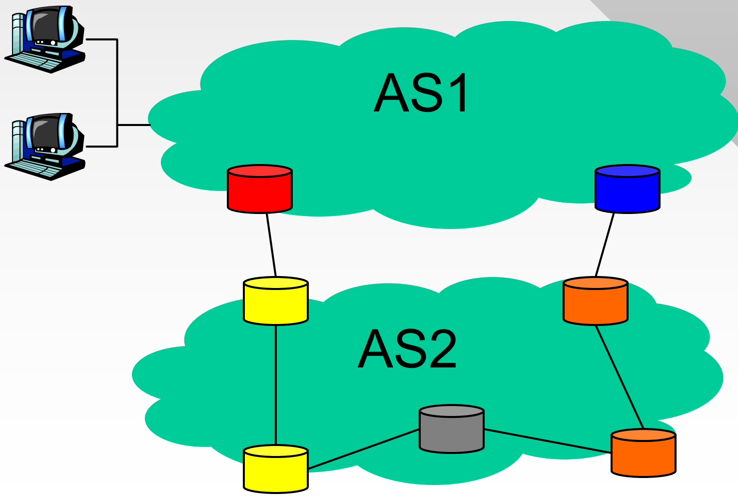
- When gateway router receives route advert, it uses an import policy to accept/decline
  - Filters and rules decide allowed/prohibited routes
- Router may learn about more than one route to some prefix, how does it decide which one is better?
  - Multi-exit discriminator (MED) attribute: policy of foreign AS that assigns different weight to different incoming points
  - Shortest AS-PATH
  - Closest NEXT-HOP router: hot potato routing
  - Local preference attribute: policy decision of accepting AS that assigns different weight to various exit points (only used in iBGP)

BGP Examples



Example 1: different MED (lower # means higher priority) for paths into AS1

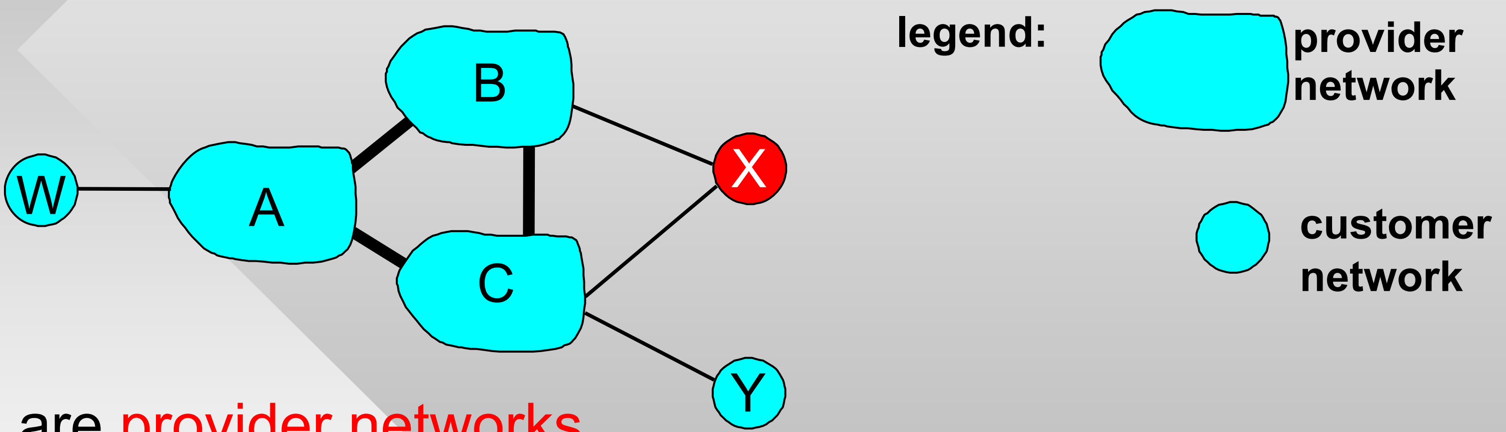
7.2.3/24: NEXT-HOP= blue, MED = 10
7.2.3/24: NEXT-HOP = red, MED = 50
192.10.3/25: NEXT-HOP= blue, MED = 50
192.10.3/25: NEXT-HOP = red, MED = 10



Example 2: hot-potato routing in AS2 (orange routers exit right, yellow left)

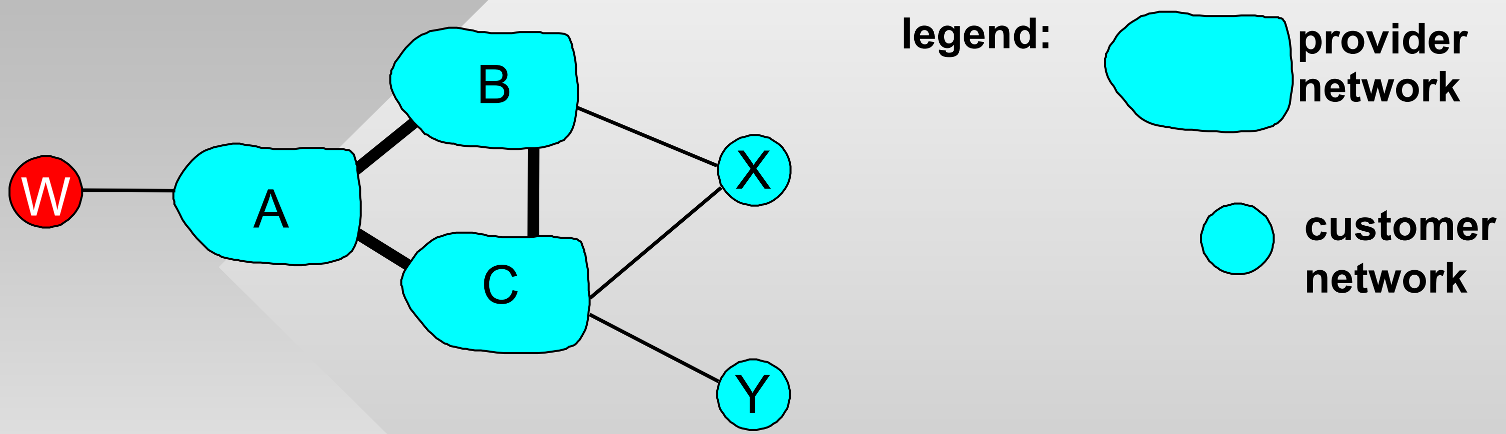
Customer BGP Policies

- BGP messages exchanged using TCP on port 179
  - Application-layer protocol



- A,B,C are provider networks
- X,W,Y are customer networks
- X is dual-homed: attached to two networks
  - X does not want to route from B via itself to C
  - .. so X will not advertise to B any routes picked up from C

Provider BGP Policies



- A advertises to B and C the path AW
- B advertises to X the path BAW
- Should B advertise to C the path BAW?
- Not unless B has agreed to route C's traffic!
  - B gets no "revenue" for routing CBAW since W, A, C are not B's customers
  - B may want to force C to route to W via A
- ISPs want to route *mainly* to/from their customers!

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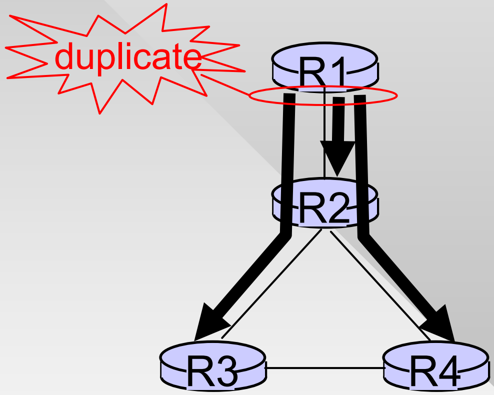
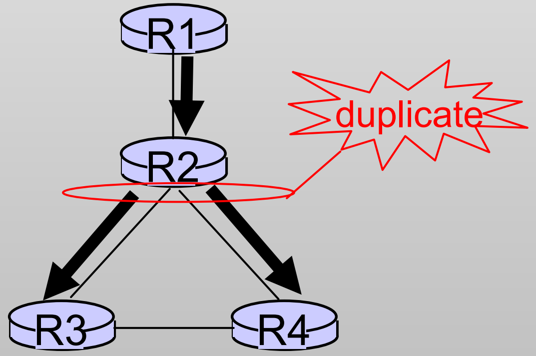
Multicast and Broadcast

- Broadcast: send a packet to all hosts in the network
- Multicast: send to a certain subset of nodes
- Unicast: one sender - one receiver



(a) unicast (5 pkt-links)

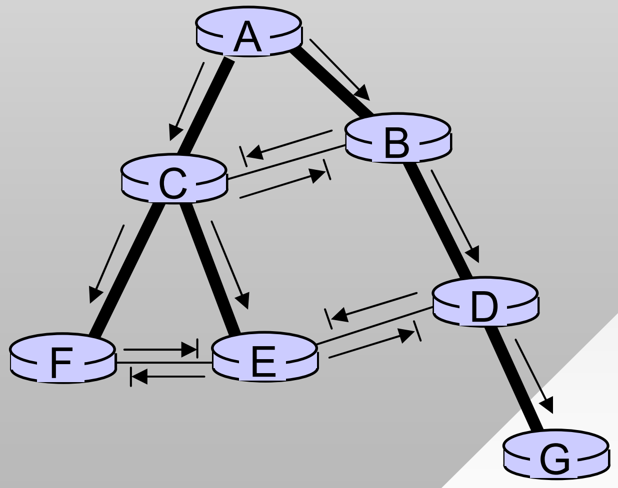


(b) multicast (3 pkt-links)

- Example: video distribution to 1M receivers via unicast
  - First link R1-R2 carries each packet 1M times
  - 5 Mbps stream requires a 5-Tbps link!

Implementing Broadcast

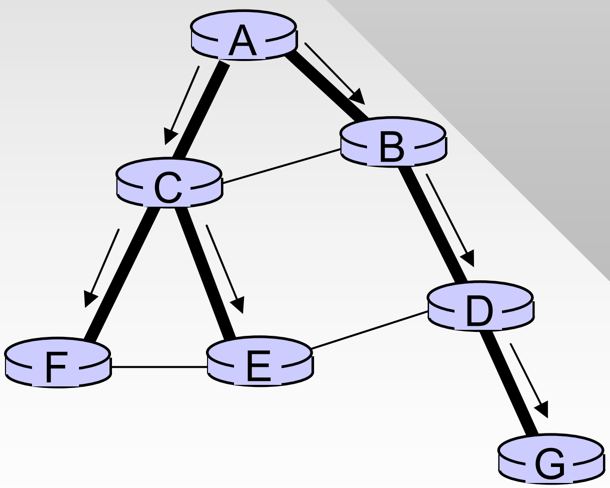
- (A) Controlled flooding: routers re-broadcast each received packet only once
  - Must keep a table of all previously received pkts to avoid re-sending of the same data (not scalable)
- (B) Reverse-path forwarding (RPF): routers re-broadcast only packets received on the interface leading towards the source along their own shortest path
- Drawbacks of RPF: redundant packets are still transmitted (e.g., C→B, B→C) and routing must be symmetric



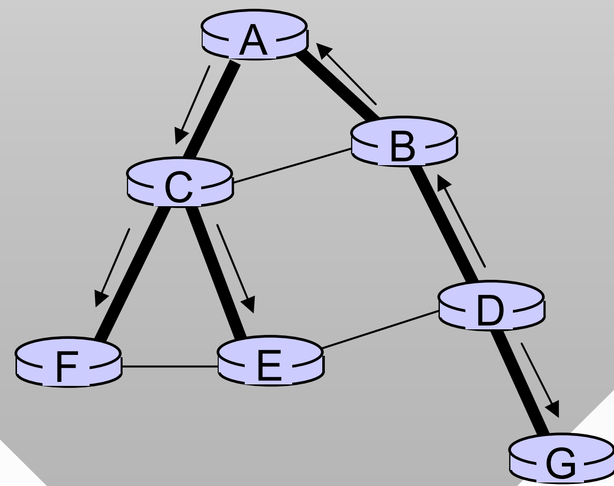
reverse path forwarding

Implementing Broadcast 2

- (C) Minimum Spanning Tree: a tree subgraph of G that spans all network nodes and has the minimum cost of all such trees
  - Once the tree is built, all data travels along the tree, regardless of the source
  - Kruskal's and Prim's algorithms build MST in $O(E \log E)$ time



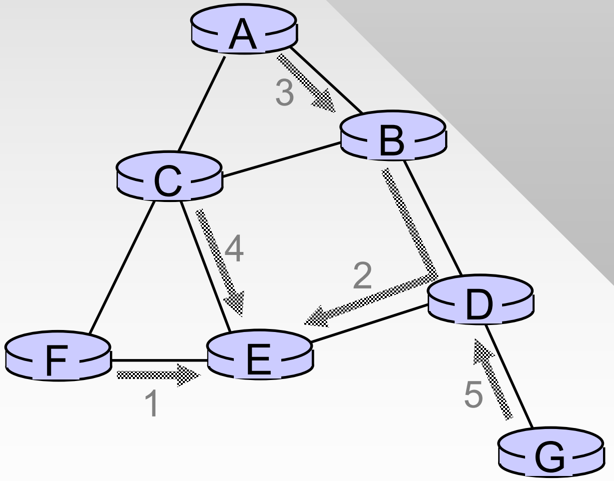
broadcast initiated at A



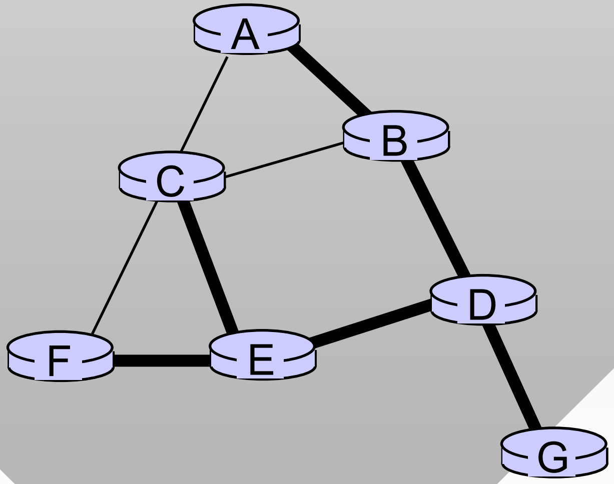
broadcast initiated at D

Construction of Spanning Trees

- MST is often impractical due to lack of global knowledge
  - Other spanning trees that approximate MST are used instead
- (D) Center-Based Spanning Tree: a “center” node is selected first (various methods exist)
  - All other nodes asynchronously send join requests using unicast routing towards the center until intersection with tree



stepwise construction of spanning tree (E is the center)



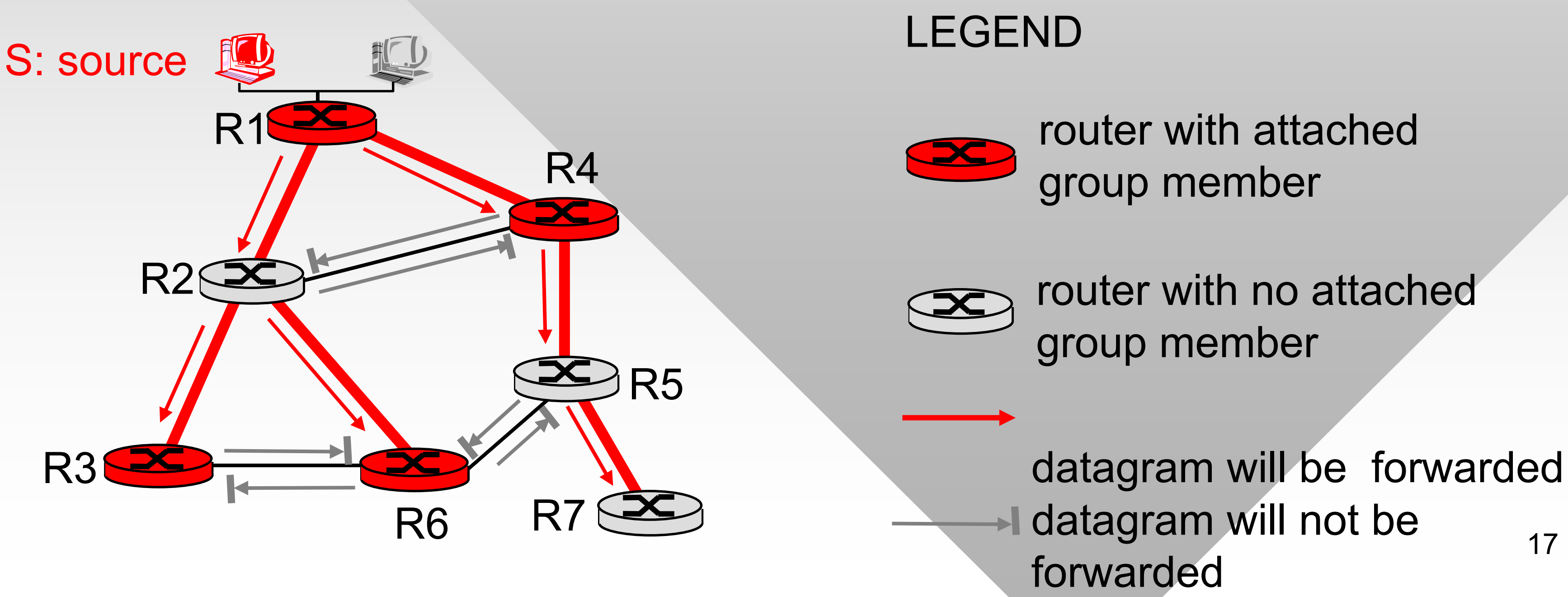
constructed spanning tree

Multicast Routing: Problem Statement

- Broadcast floods the entire Internet and is expensive; in contrast, multicast involves a subset of routers
- Applications
  - Video/audio conferencing: participants form a multicast group to generate and consume content (many-to-many)
  - Video-on-demand or pay-per-view: multicast group is formed by one server and many receivers that consume pre-recorded content (one-to-many)
  - Patch distribution: OS provider distributes updates to hosts running its kernel (one-to-many)
  - Live TV: content received from video provider via multiple servers and fed to many receivers (many-to-many)
- ***Goal:*** create a tree between routers to which multicast group members are attached

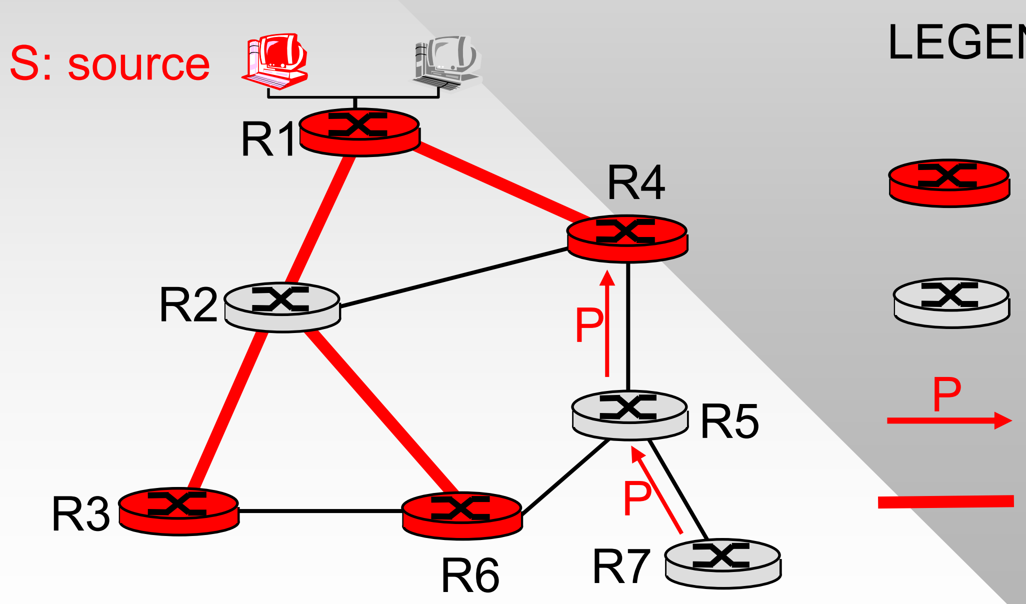
Approaches to Building Mcast Trees

- (A) Source-based mcast forwarding tree: tree of shortest path routes from source S to all receivers
  - Dijkstra's algorithm when S knows entire topology from some link-state routing algorithm (e.g., MOSPF)
- (B) Source-specific RPF (default opt-in)
  - Initially flood every router (even if R2, R5, R7 don't want it)



Approaches to Building Mcast Trees

- Forwarding tree may contain subtrees with no mcast group members
  - No need to forward datagrams down subtree
  - “Prune” msgs sent upstream by router with no downstream group members



Approaches to Building Mcast Trees

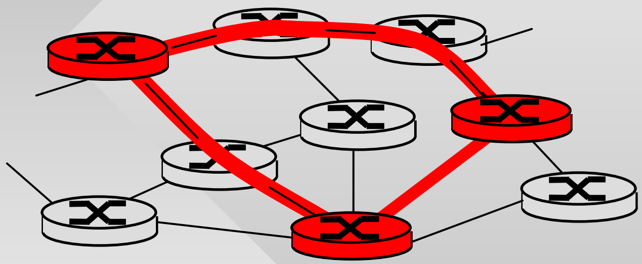
- (C) Steiner Tree: minimum cost tree connecting all routers with attached group members
  - Problem is NP-complete
- Even though heuristics exists, not used in practice:
  - Global information about entire network needed
  - Computational complexity
  - Monolithic: rerun whenever a router needs to join/leave
- (D) Center-Based Tree (CBT) (default opt-out)
  - Single delivery tree shared by all
  - One router identified as "center" of tree
  - Join messages sent towards center until existing tree is met

Internet Multicast Routing: DVMRP

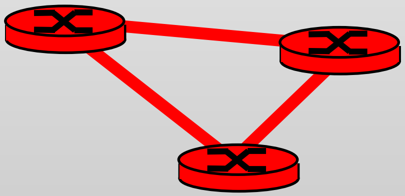
- DVMRP: Distance Vector Multicast Routing Protocol, RFC 1075 (1988)
- *Flood and prune (default opt-in):* reverse path forwarding (RPF), tree rooted at source
  - RPF tree based on DVMRP's own routing tables constructed by communicating DVMRP routers
  - No assumptions about underlying unicast
  - Initial datagram to mcast group flooded everywhere via RPF
- IGMP broadcasts proceed between neighbor routers
- Multicast IP addresses are in 224.0.0.0/4
  - To join a particular group, use setsockopt with IP_ADD_MEMBERSHIP

Tunneling

Q: How to connect "islands" of multicast routers in a "sea" of unicast routers?



physical topology



logical topology

- Mcast datagram encapsulated inside "normal" (non-multicast-addressed) datagram
  - Unicast IP datagram sent thru "tunnel" via regular IP unicast to receiving mcast router
  - Receiving mcast router decapsulates mcast datagrams

PIM: Protocol Independent Multicast

Dense (default opt-in):

- Group membership by routers assumed until routers explicitly prune
- Data-driven construction of mcast tree (e.g., RPF)
- Bandwidth and non-group-router processing assumed sufficient

Sparse (default opt-out):

- No membership until routers explicitly join
- Receiver-driven construction of mcast tree (e.g., center-based)
- Bandwidth and non-group-router processing is conservative

Multicast Future

- Wide-area multicast deployment has been traditionally slow, now practically dead
  - Mbone was one such endeavor, worked via tunnels
- One issue is scalability
  - Flooding all Internet receivers is dangerous/expensive
  - Opens loopholes for DoS attacks
- Another is ISP unwillingness to accept multicast traffic
  - Who pays for a single packet being replicated 1M times?
- Finally, multicast congestion control is hard
  - Mbone had 30-40% loss, which is much more than most applications can tolerate (typically below 1%)
  - How to recover lost packets?