

**Problem: There is more than one network
(heterogeneity & scale)**

Internetworking:

- Internet Protocol (IP)
- Routing and scalability
- Group Communication

Internetworking

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Every seeming equality conceals a hierarchy.

--- Mason Cooley

Acknowledgement: this lecture is partially based on the slides of Dr. Larry Peterson

Process Groups

- Example uses
 - data dissemination (e.g., news)
 - replicated servers
- Group properties
 - Any set of processes that want to cooperate
 - Processes can join/leave either implicitly or explicitly
 - A process can belong to many groups
- Use multicast rather than point-to-point messages
 - group name (address) provides a useful level of indirection

Outline

- Multicast Routing

- A digression: replication of state machine
 - An application of multicast in improving systems dependability

Outline

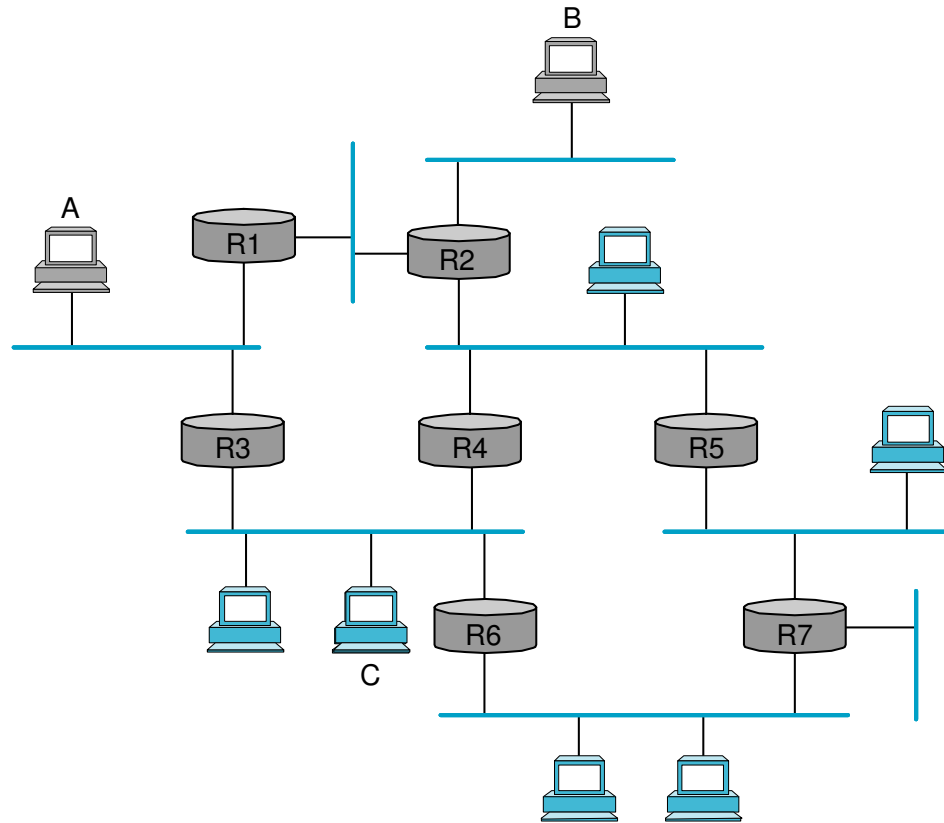
- Multicast Routing

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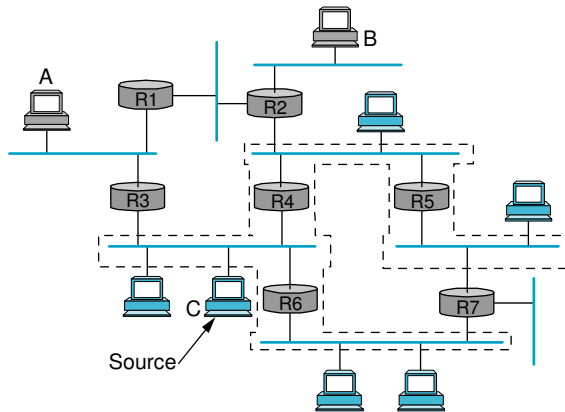
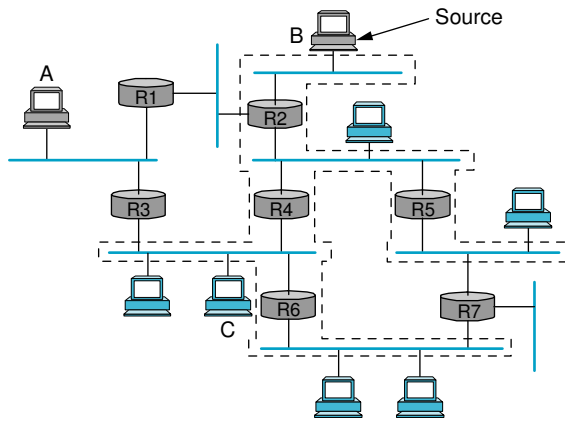
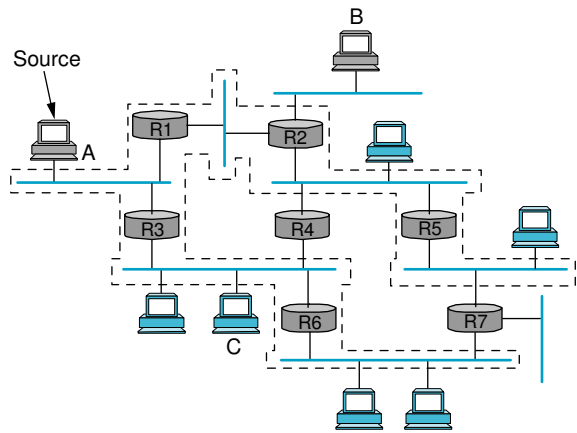
Multicast Routing: Link State

- Each host on a LAN periodically announces the groups it belongs to using Internet Group Management Protocol (IGMP)
- Augment update message (LSP) to include set of groups that have members on a particular LAN
- Each router uses Dijkstra's algorithm to compute shortest-path spanning tree for each source/group pair

Example of LS multicast routing



Example internet with members of group G in color



Example of shortest-path multicast trees

Scalability issue of L-S multicast routing

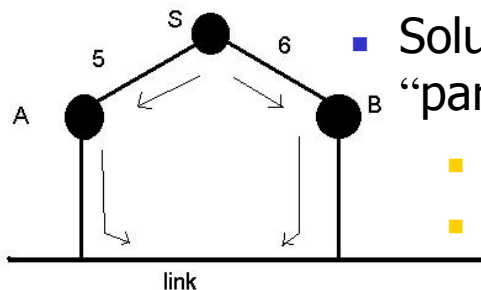
- (in addition to scalability issues of LS routing) Need to maintain the shortest-path routing tree for each source-group pair
 - Will consume too much memory
- Ameliorating approach: each router only caches trees for currently active source/group pairs
 - (-) With added computation cost when a group transits from “inactive” to “active” (this may well be affordable); similar to the caching issue in computer memory system

Multicast Routing: Distance Vector (D-V)

- Reverse Path Broadcast (RPB)

- Each router already knows that its shortest path to source node S goes through a neighboring router, say N; then
- When receive multicast packet from S, forward on all outgoing links (except one it arrived on), iff. packet arrived from N

- (-) a given packet will be forwarded over a LAN by each of the routers connected to that LAN



- Solution: eliminate duplicate broadcast packets by letting only “parent” for LAN (relative to S) forward

- shortest path to S (learn from distance vector): e.g., A
- smallest address to break ties

D-V multicast (contd.)

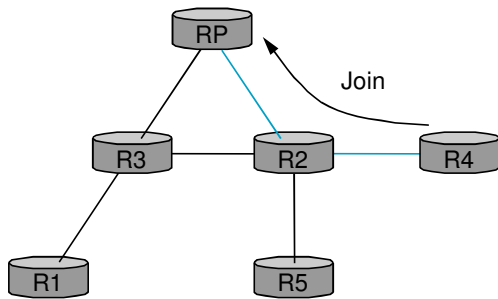
- Reverse Path Multicast (RPM)
 - Goal: prune networks (from RPB tree) that have no hosts in group G
 - Step 1: determine if LAN is a *leaf* with no members in G
 - leaf if parent is the only router on the LAN
 - determine if any hosts are members of G using IGMP
 - Step 2: “propagate” “no members of G here” information up along the tree
 - augment (destination, cost) update sent to neighbors with set of groups for which this network is interested in receiving multicast packets
 - To avoid high memory overhead, only happens when multicast address becomes active (i.e., first use RPB, then prune unnecessary subtrees)

Protocol independent multicast (PIM)

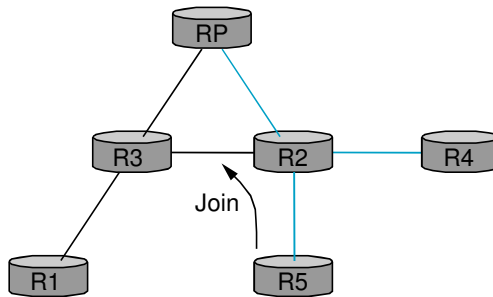
- Deals with inefficiency of existing multicast routing protocols (especially D-V multicast) when groups only consist of a small percentage of routers
 - E.g., the (initial) broadcast in RPB (RPM)
- Two modes
 - Sparse mode: PIM-SM
 - Dense mode: PIM-DM (similar to RPM)

PIM-SM

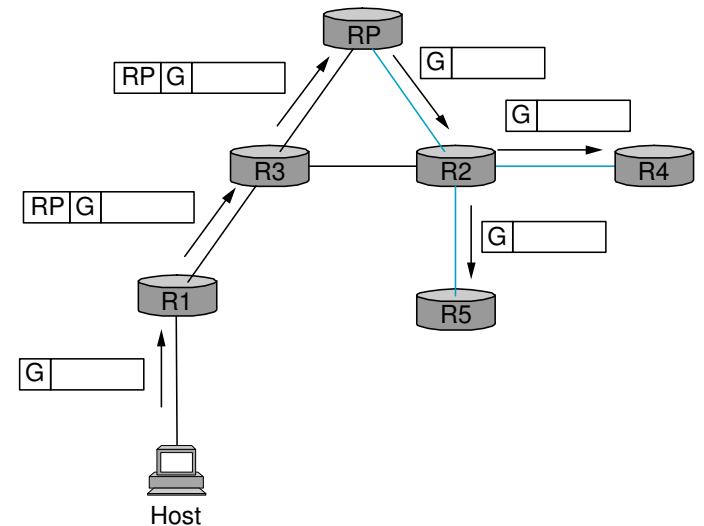
- Each group is assigned a rendezvous point (RP)
 - Acts as the central relay between "source" and "group"



R4 sends Join to RP and joins shared tree



R5 sends Join to RP and joins shared tree: R2 does not forward Join to RP since it knows link (RP, R2) has been a part of the shared tree

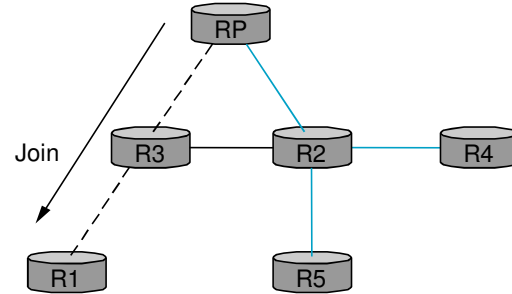


Source R1 tunnels the multicast packet to RP, which forwards it along the shared tree to R4 and R5

- RP = Rendezvous point
- Shared tree
- Source-specific tree for source R1

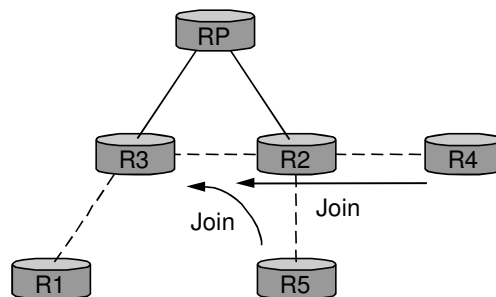
PIM-SM: optimization (e.g., when there is a lot of data traffic to the group)

- Avoid overhead incurred by “tunneling from source to RP”



RP builds source-specific tree to R1 by sending Join to R1

- Avoid the increased path length (or tree depth) due to transmission relay via RP



R4 and R5 build source-specific tree to R1 by sending Joins to R1

Note on PIM

- PIM is “protocol independent” in terms of “unicast routing protocol independent”
 - Unicast used in tree maintenance (e.g., delivery of “Join” message)
- It is pretty much bound with the Internet Protocol --- it is NOT protocol independent in terms of network-layer protocols

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High availability via Replicated State Machine

- Service is characterized as a state machine that modifies variables in response to outside operations
- State machine is replicated to improve availability
- Key is ensuring
 - all operations are atomic (applied at all functioning replicas)
 - all replicas remain consistent (ops applied in same order)
- Implementation
 - encapsulate operations in messages
 - send using group communication

Atomic Messages

- Atomicity property: a message is delivered to all members, or to none
- First try...
 - each recipient acknowledges message
 - sender retransmits if ACK not received
 - problem: sender could crash before message is delivered everywhere

Atomic Messages (contd.)

- Fix: if sender crashes, a recipient volunteers to be “backup sender” for the message
 - re-sends message to everybody, waits for ACKs
 - use simple algorithm to choose volunteer
 - apply method again if backup fails
- Must remember all received messages in case we need to become backup sender
 - periodic protocol to “prune” old messages
 - how to know it's safe to prune?

Message Ordering

- So far: different members may see messages in different orders
- Ordered group communication requires all members to agree about the order of messages
- Within group, assign global ordering to messages
- Hold back messages that arrive out-of-order

Ordering: First Approach

- *Central ordering server* assigns global sequence numbers
- Hosts apply to ordering server for numbers, or ordering server sends all messages itself
- Have to deal with case where ordering server fails
 - leader election we saw earlier
- Hold-back easy since sequence numbers are sequential

Ordering: Second Approach

- Use *time* when message was sent
 - measured on sending host
 - use host address to break ties
- Advantage
 - simple and decentralized
- Disadvantage
 - requires nearly synchronized clocks
 - must hold back messages for a period equal to maximum clock difference

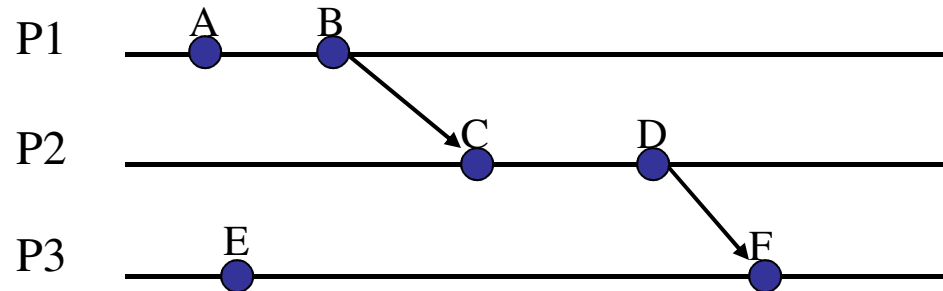
Logical Time

- Insight: often don't care about when something happened, only about which thing happened first
- Happened before relationship
 - $X < Y$ means “X happened before Y”
 - three rules:
 - if X and Y occur in the same process and X occurs before Y, then $X < Y$
 - if M is a message, then $\text{send}(M) < \text{receive}(M)$
 - if $X < Y$ and $Y < Z$, then $X < Z$

Logical Time (contd.)

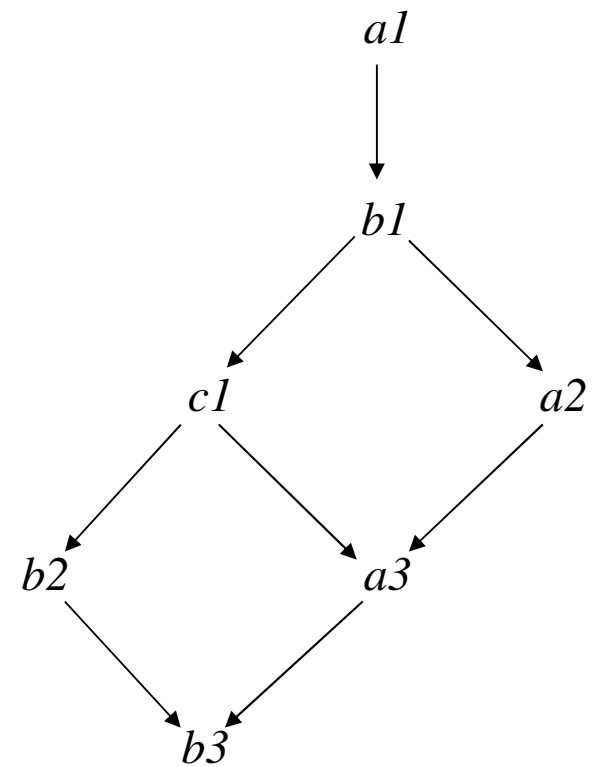
- Given two events X and Y , either
 - $X < Y$, or
 - $Y < X$, or
 - neither (X and Y are concurrent)
- $<$ relation defines a partial order

- Example



Message Context to implement logical time

- Key: how to identify *partial order*?
- A process sends a message *in the context of* all the messages it has received.
- Group communication represented with a *context graph*.
- Example: 3 senders, denoted a , b , and c



Protocol

- Each node maintains a copy of the context graph
 - union of all copies equals “global graph”
- Send:
 - message-id (sender, seqno)
 - message-id of all predecessor messages
 - Only need to send *leaves* of sender’s copy of context graph
 - bounded by number of participants (why?)
- Receive:
 - add the partial context graph to local copy
 - deliver message to application
 - hold back if not all predecessors are present
 - ask sender to retransmit missing messages (why?)
 - pass up to application in “context” order

Protocol (contd.)

- Applications can inspect context graph
 - leaves, precedes, root, stable
- Message stability
 - A message is stable if it is followed by a message from all other participants
- System can free all stable messages from its copy
 - will never be asked to retransmit them

Host Failures

- How to guarantee
 - all running processes are able to continue exchanging messages
 - a message contained in any running host's copy will eventually be incorporated into every running host's copy

- Application support
 - mask out failed processes
 - adjusts message stability

Message Order

- Context graph preserves partial order among messages
- Each host can produce same total order by running a topological sort on context graph (with “tie-breaking” mechanism to order “concurrent packets”)
 - incremental since messages continually arriving
- Commit next “wave” of messages to application as soon as one message in wave becomes stable
 - know that no future messages will be at same logical time

Summary of Internetworking

- Internet Protocol (IP)
 - Best Effort Service Model
 - Global Addressing Scheme
 - Common IP format; datagram forwarding

 - Address translation (ARP)

 - Host configuration (DHCP)
 - Error reporting (ICMP)
 - Virtual private networks and IP tunnels
- Routing and algorithms
 - Algorithms: D-V, L-S, metrics, Mobile IP
 - Scalability: subnetting, supernetting (CIDR), BGP (P-V), IPv6
- Group communication
 - Multicast routing: L-S, D-V (RPB, RPM), PIM-SM
 - Atomic and ordered messaging

Discussion

- Routing in wireless networks (e.g., mesh networks, sensor networks, MANETs, etc)
 - Link quality estimation, Routing metric
 - Alec Woo, Terence Tong, and David Culler, Taming the Underlying Challenges of Reliable Multihop Routing in Sensor Networks, ACM SenSys'03
 - R. Draves, J. Padhye, and B. Zill, *Routing in Multi-radio, Multi-hop Wireless Mesh Networks*, ACM MobiCom'04
 - Hongwei Zhang, Anish Arora, and Prasad Sinha, *Learn on the Fly: Data-driven Link Estimation and Routing in Sensor Network Backbones*, IEEE INFOCOM'06

Discussion (contd.)

- Routing in mobile ad hoc networks
 - AODV, DSR, OLSR, etc.
 - IETF Manet working group:
<http://www.ietf.org/html.charters/manet-charter.html>
- Routing in disruption(delay)-tolerant networks
 - Delay Tolerant Networking Research Group:
<http://www.dtnrg.org/wiki>
 - Standards, papers ...: <http://www.dtnrg.org/wiki/Docs>
 - Code: <http://www.dtnrg.org/wiki/Code>

Discussion (contd.)

- Multicast routing
 - Fault tolerant distributed algorithms for minimum-spanning tree (instead of shortest-path spanning tree)
 - Harder especially for wireless and mobile networks where we have high degree of network dynamics
 - IETF Multicast & Anycast Group Membership:
<http://www.ietf.org/html.charters/magma-charter.html>
 - IETF Multicast Security: <http://www.ietf.org/html.charters/msec-charter.html>
 - IRTF Secure Multicast Research Group:
<http://www.securemulticast.org/smug-index.htm>

Further reading

- TCP/IP architecture (2004 Turing Award!)
 - V. Cerf and R. Kahn, A Protocol for Packet Network Interconnection, IEEE Transactions on Communications, 22(5):637-648, May 1974.
- Scalability issue of IPv4, and IPv6
 - S. Bradner and A. Mankin, The Recommendation for the Next Generation IP Protocol, RFC 1752, Jan. 1995
- Internet routing behavior
 - V. Paxson, End-to-end Routing Behavior in the Internet, ACM SIGCOMM'96

Further reading (contd.)

- Multicast routing
 - S. Deering and D. Cheriton, Multicast Routing in Datagram Internetworks and Extended LANs, ACM Transactions on Computer Systems, 8(2), May 1990
- IETF (Internet Engineering Task Force)
 - <http://www.ietf.org>
 - RFCs, Internet Drafts, and working group charters

Assignment – Chapter 4

- Lab#2 (mandatory)
 - Study the source code of CTP in TinyOS distribution, and figure out how link estimation and distance-vector routing is implemented in real-world source code
 - Measure the packet delivery reliability of CTP in a multi-hop wireless network of 7*7 grid whose average link reliability is 90%

- Exercise#3
 - Exercises 4, 15, 17, 20, 21, 40, 44, 45, 60

- Quiz#3