Multicast routing principles in Internet

Motivation

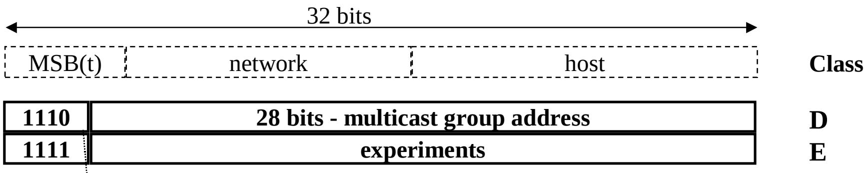
Recap on graphs

Principles

Multicast capability has been and is under intensive development in the 1990's

- MBONE used to multicast IETF meetings from 1992
- Extends LAN broadcast capability to WAN in an efficient manner
- Valuable applications
  - resource discovery
  - network load minimization by replacing many pt-to-pt transmissions
  - multimedia conferencing

Multicast addresses



224.0.0.0 - 239.255.255.255

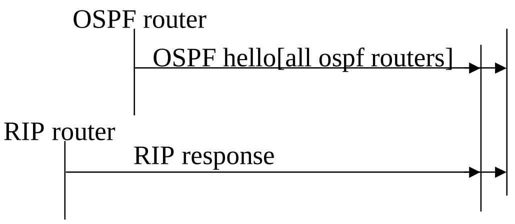
224.0.0.1	All systems
224.0.0.2	All routers
224.0.0.4	All DVMRP routers
224.0.0.1 - 224.0.0.255	Local segment usage only
239.0.0.0 - 239.255.255.255	Admin scoped multicast (local significance)
239.192.0.0 - 239.195.255.255	Organisation local scope

Ethernet MAC address: MACprefix+G --> no lookup, no ARP

Note: + Sender does not need to belong to G.

+ Address space is flat!

Resource discovery by MC simplifies network management

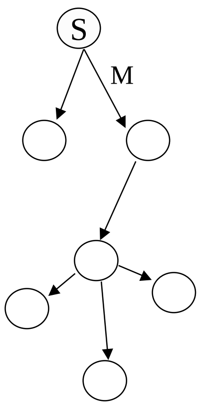


- No need for lists of neighbors, just use std MC address
- How to find corporate DNS -server --> MC to all nodes in corporate network.
- Network is easily flooded with messages.
- TTL can be used for Broadcast scope limitation
  - --> find nearest DNS or whatever
  - -- when TTL=0, router does not return ICMP msg!

Conferencing requirements include

- Multiple sources, multiple recipients, multiple media
- Variable membership
- Small conferences with intelligent media control (what is sent to where)
- Large conferences require media processing in special devices

Multipoint sessions differ from point-to-point communication

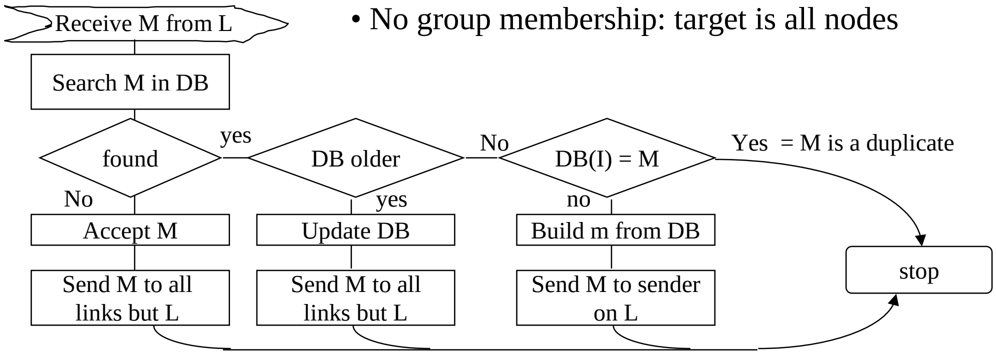


- Participants may join and leave the session.
- Receiver-makes good principle instead of session parameter negotiation.
- Window based flow control does not apply:
  -- use UDP / connectionless protocols

Flooding is the simplest MC algorithm

Flooding algorithm is

- Need to keep state (DB) in nodes!
- No group membership: target is all nodes



- Examples: OSPF, usenet news...

Alternative to DB in flooding is trace info in the message

- Trace info in Message lists all passed nodes
- Avoids a costly DB reads but may accept same M several times.
- If neighbor is in trace, does not send

Flooding guarantees that node will not forward the same packet twice. It does not guarantee that node will receive the same packet only once! --> Greedy algorithm.
+++Does not depend on routing tables -->robust

Networks are modeled as Graphs.

G = (V, E),

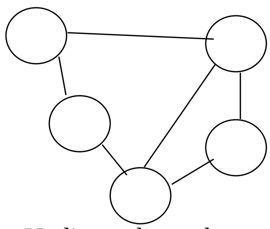
V - set of **vertices or nodes** (non-empty, finite set)

E = {e_j | j = 1, 2, … M} - set of **edges or links.**

$$e_j = (v_i, v_k) = (i, k)$$

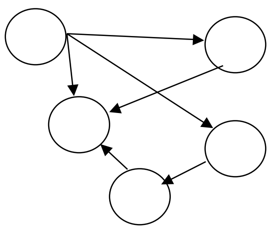
Nodes i and k are **adjacent** if link (i, k) exists.
Nodes i and k are also called **neighbors**.

Links are bi-, arcs are unidirectional



Undirected grapth

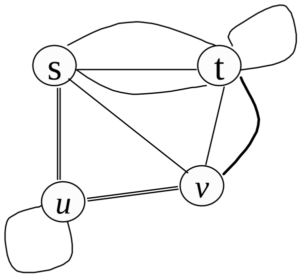
Degree of a node is the number of its neighbors or the number of links **incident on the node**.



Directed graph

Unidirectional links,
$a_j = (v_i, v_k) = [i,k]$ are called **arcs**.
If links and nodes have properties, the graph is called a **network**.

Graphs with parallel links are called multigraphs



Links between a node and itself are **self loops**.

Graph with no parallel links and no self loops is a **simple graph**.

A **path** in a network is a sequence of links beginning at some node s and ending at some node t. = **s,t-path**. If s = t, path is called a **cycle**. If an intermediate node appears no more than once, it is a **simple cycle**.

Graph is **Connected** if there is at least one path between every pair of nodes.

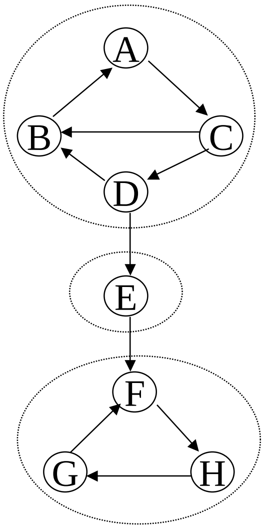
- A subset of nodes with paths to one another is a connected component.

Reflective: By def. ∃ i,i-path
Symmetric: ∃ i,j-path ⇒ ∃ j,i-path
Transitive: ∃ i,j-path and ∃ j,k-path ⇒ ∃ i,k-path

⇒ Components are equivalence classes and the component structure is a partition of the graph.

Partition applies to links and nodes alike.

A directed graph is **strongly connected** if there is a **directed path** from every node to every other node.



- Directed connectivity is not symmetric.
- A subset of nodes with directed paths from any one node to any other is a **strongly connected component**.
- A node belongs to exactly one strongly connected c. An arc is part of *at most one* strongly connected c.

A **tree** is a graph without cycles

- Given a Graph $G = (V, E)$, H is a subgraph of G if $H = (V', E')$ where $V' \subset V$ and $E' \subset E$
- A **spanning tree** is a connected graph without cycles.
- If graph is not necessarily connected, we talk about **a forest**.

Spanning trees model minimally connected networks

- ST is a minimum cost network.
- Only a single path exists between any two nodes in a ST --> routing is trivial.
- If a graph has N nodes, any tree spanning the nodes has exactly N - 1 edges.
- Any forest with k components has exactly N - k edges. (proof by induction starting from graph with no edges).

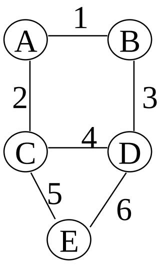
A set of edges whose removal disconnects a graph is called a **disconnecting set.**

- **XY-cutset** partitions a graph to subgraphs X and Y.
- In a tree any edge is **a minimal cutset**.
- A minimal set of nodes whose removal partitions the remaining nodes into two connected subgraphs is called **a cut**.

Suomalaiset graafitermit

Vertex, node	- kärki,solmu
Edge, link	- syrjä, linkki, sivu, kaari, haara
Adjacent	- viereinen
Neighbor	- naapuri
Degree of a node	- solmun aste(?)
Arc	- kaari
Cycle, Loop	- silmukka
Path	- polku
Directed path	- suunnattu polku
Connected	- yhteydellinen, yhdistetty
Strongly connected	- vahvasti yhteydellinen
Subgraph	- aligraafi
Tree	- puu
Spanning tree	- virittäjäpuu
Forest	- metsä
Disconnecting set	- erotusjoukko
Cut	- leikkaus
XY-cutset	- XY-leikkaus-joukko

Adjacency and Incidence Matrices are used to present Graphs



Node

Node	A	B	C	D	E
A	0	1	1	0	0
B	1	0	0	1	0
C	1	0	0	1	1
D	0	1	1	0	1
E	0	0	1	1	0

Adjacency Matrix

Link

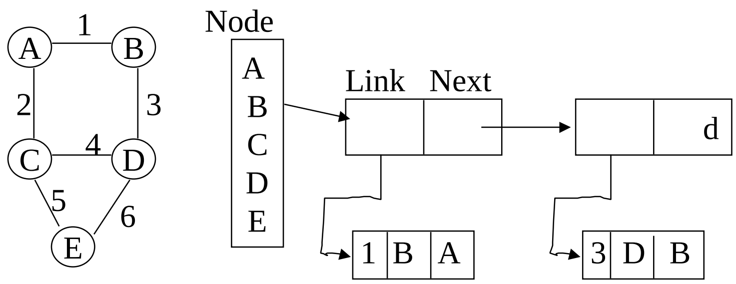
Node	1	2	3	4	5	6
A	1	1	0	0	0	0
B	1	0	1	0	0	0
C	0	1	0	1	1	0
D	0	0	1	1	0	1
E	0	0	0	0	1	1

Incidence Matrix

For an undirected graph
Adjacency matrix is symmetric.

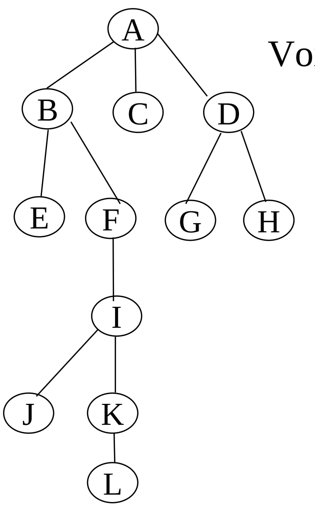
For directed graphs +1 is
source and -1 is sink of an arc

For graph algorithms linked list presentation of adjacency is convenient



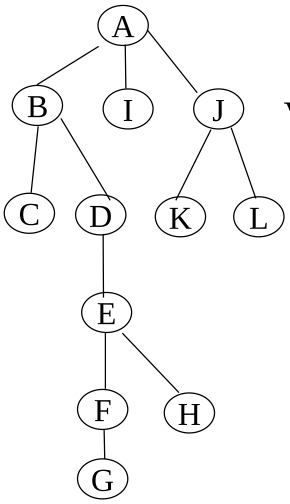
A Tree can be traversed by Breadth-first-search

Works for directed links




```
Void <- BfsTree( n, root, n_adj_list )
    dcl n_adj_list [n, list]  /* array of lists of neighbors
        scan_queue [queue]
    InitializeQueue( scan_queue)
    Enqueue(root, scan_queue)
    while NotEmpty(scan_queue)
        node <- Dequeue(scan_queue)
        Visit (node)
        for each (neighbor, n_adj_list[node])
            Enqueue(neighbor, scan_queue)
```

A Tree can also be traversed by Depth-first-search



Works for directed links

```
Void <- DfsTree( n, root, n_adj_list )
     dcl n_adj_list [n, list]

     Visit (root)
      for each (neighbor, n_adj_list[node])
           DfsTree(n, neighbor, n_adj_list)
```


An undirected graph can be traversed by Depth-first-search

```
Void <- Dfs ( n, root, n_adj_list )
     dcl n_adj_list [n, list]
          visited[n]              /* keeps track of progress
     void <- DfsLoop(node)
          if not visited[node]
               visited[node] <- TRUE
               Visit (node)
               for each (neighbor, n_adj_list[node])
                    DfsLoop(neighbor)
     visited <- FALSE
     DfsLoop( root )
```

We can now find and label the connected components of an arbitrary graph

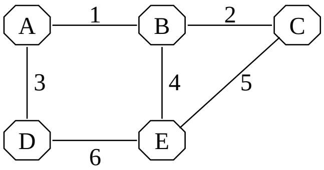
```
Void <- LabelComponents(n, n_adj_list)
    dcl n_component_nr[n], n_adj_list[n, list]
    void <- Visit(node)
        n_component_nr[node] <- ncomponents
    n_component_nr <-   0
    ncomponents <-  0
    for each ( node, nodeset )
        if  (n_component_nr[node] = 0
            ncomponents +=1
            Dfs( node, n_adj_list )
```

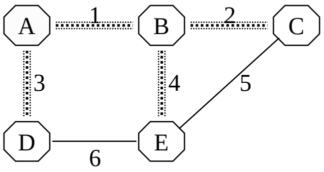

Minimum Spanning Tree is the ST with minimum cost

- We assign a length to each edge of the graph. “Length” can be distance, cost, a measure of delay or reliability.
- We look for minimum total length/cost, thus we talk about MST.
- If the graph is not connected, we may look for a minimum spanning forest.

$n = c + e$, where n is the number of nodes, c the number of components and e number of edges selected so far holds always.

MC to a *spanning tree* leads to reception only once in each node





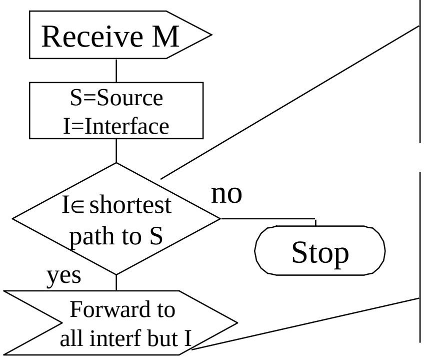
- Requires on/off bit ($\in$ ST) per link
- No group membership
- Concentrates traffic to the STlinks
- Ideal would be a tree that
  - spans the group members only
  - minimizes state information in nodes
  - optimizes routes based on metrics

A Greedy MST algorithm

```
List <- Greedy( properties )
   dcl properties [list, list],
        candidate_set[list], solution[list]

   void <- GreedyLoop( *candidate_set, *solution)
      dcl test_set[list], candidate_set[list], solution[list]

      element <- BestElementOf(candidate_set)   /* for MST: shortest edge
      test_set <- element ∪ solution
      If test_set is feasible                    /* for MST: no cycles
         solution <- test_set
      candidate_set <- candidate_set \ element
      If candidate set is not Empty
         Greedy_Loop( *candidate_set, *solution)

solution <- ∅
If (candidate_set <- ElementsOf(properties)) is not Empty
    GreedyLoop( *candidate_set, *solution)
return(solution)
```

Reverse-Path Forwarding computes an implicit spanning tree per source, is OK for dense trees

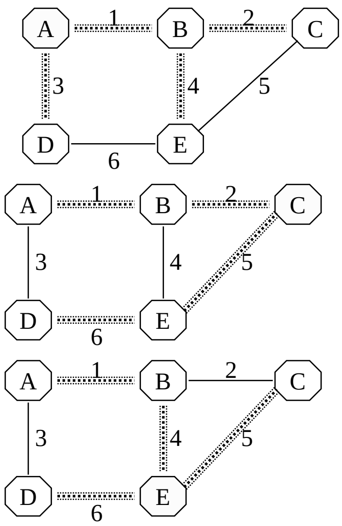
• RPF was first used in MBone



Note: path is computed
from S to node.
In symmetric networks =
path from node to S

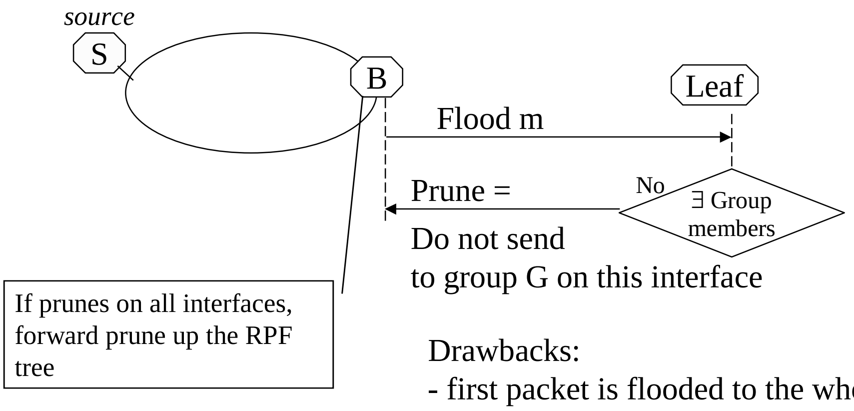
Looking one step further: send only if
our Node is on shortest path
from S to next Node.
Requires 1 bit/source and /link
in link state DB

Reverse path forwarding properties



- No group membership but can be scoped by TTL
- Guarantees fastest possible delivery since uses shortest paths only
- Different tree for each source --> traffic is spread over multiple links leading to better network utilization

“Flood and prune” introduces dynamic group membership



Drawbacks:
- first packet is flooded to the whole net
- nodes must keep state per S and G.
- state is transient (timed out)

Steiner tree spans the group with the minimal cost according to link metrics

- Has never actually been used, only simulated:
  – Finding the mimimum Steiner tree in a graph has exponential complexity and result is not necessarily optimal
  – The tree is undirected: links must be symmetrical
  – Algorithm is monolithic, can’t be distributed
  – The tree is unstable when changes occur: traffic routes change dramatically when e.g a member leaves.
- Popular because of its mathematical complexity
- Leads to Center based approach (CBT, PIM)