# Lectures 18: Routing in Data Networks

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# Routing

- **Must choose routes for various origin destination pairs (O/D pairs) or for various sessions**

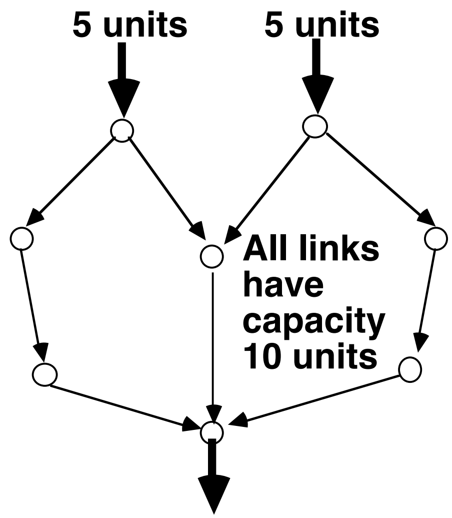
  – **Datagram routing: route chosen on a packet by packet basis**

    **Using datagram routing is an easy way to split paths**

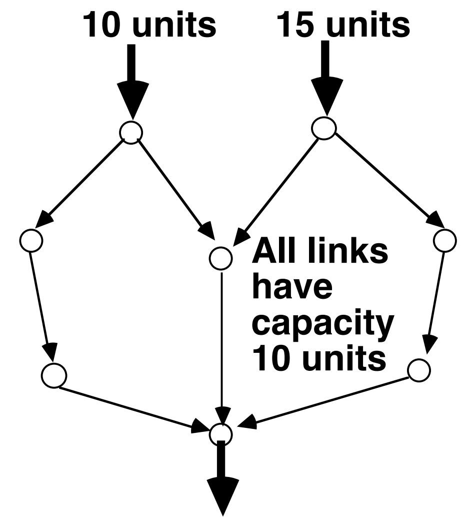
  – **Virtual circuit routing: route chosen a session by session basis**

  – **Static routing: route chosen in a prearranged way based on O/D pairs**

# Routing is a global problem




Either session alone is best routed through center path, but both cannot go through center.




Both sessions must split their traffic between two paths.

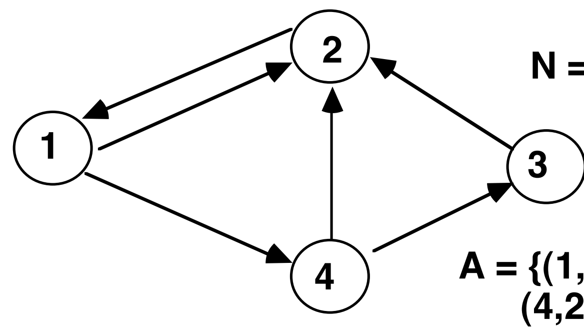
- **Static routing is not desirable**
- **Datagam routing is a natural way to split the traffic**
  - **How?**

# Shortest Path routing

- Each link has a cost that reflects
  - The length of the link
  - Delay on the link
  - Congestion
  - $$ cost
- Cost may change with time
- The length of the route is the sum of the costs along the route
- The shortest path is the path with minimum length
- Shortest Path algorithms
  - Bellman-Ford: centralized and distributed versions
  - Dijkstra's algorithm
  - Many others

# Directed graphs (digraphs)

- A directed graph (digraph) G = (N,A) is a finite nonempty set of nodes N and a set of ordered node pairs A called directed arcs.




N = {1,2,3,4}

A = {(1,2), (2,1),(1,4),
(4,2), (4,3),(3,2)}

- Directed walk: (4,2,1,4,3,2)
- Directed path: (4,2,1)
- Directed cycle: (4,2,1,4)
- Data networks are best represented with digraphs, although typically links tend to be bi-directional (cost may differ in each direction)
  – For simplicity we will use bi-directional links of equal costs in our examples

# Bellman Ford algorithm

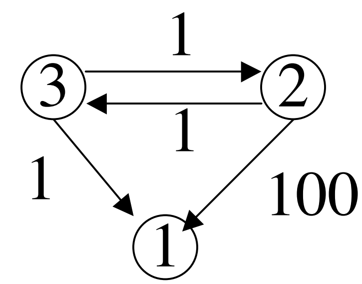
- **Finds the shortest paths, from a given source node (1) to all other nodes**
- **General idea:**
  - **First find the shortest single arc path,**
  - **Then the shortest path of at most two arcs, etc.**
  - **Let $d_{ij}=\infty$ if (i,j) is not an arc.**
- **Let $D_i(h)$ be the shortest distance from 1 to i using at most h arcs**
  - $D_i(1) = d_{1i}$ ; $i \neq 1$ $\quad$ D1(1) = 0
  - $D_i(h+1) = \min \{j\} [D_j(h) + d_{ji}]$ ; $i \neq 1$ $\quad$ $D_1(h+1) = 0$
- **If all weights are positive, algorithm terminates in N-1 steps**

# Bellman Ford - example

# Distributed Bellman Ford

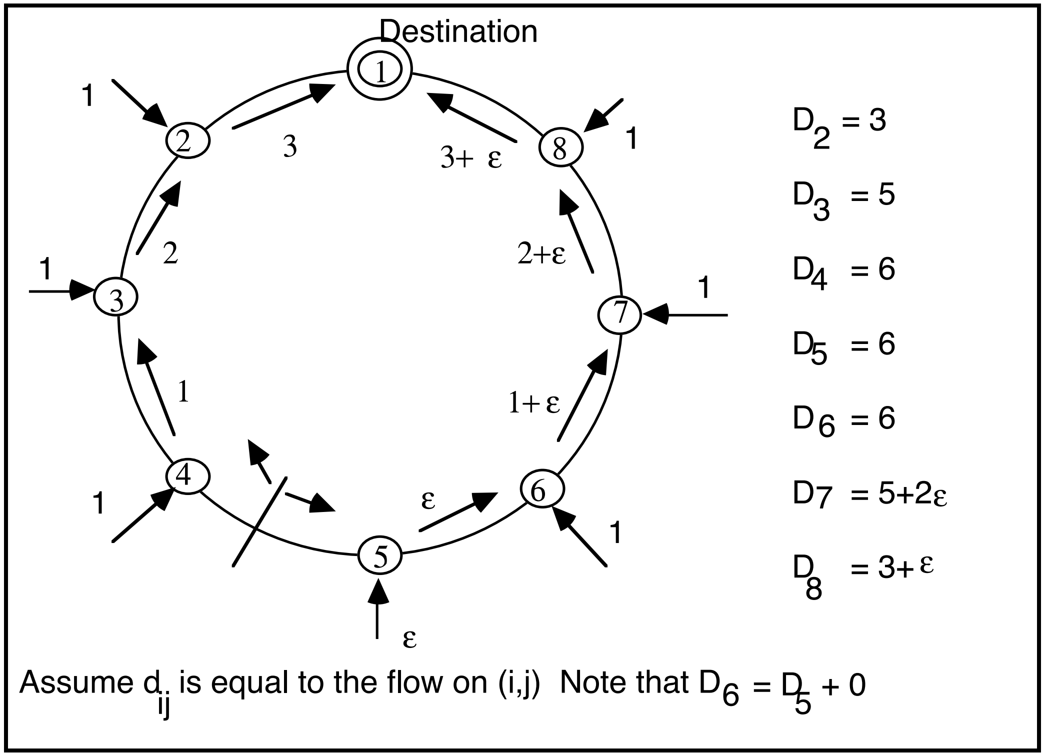
- Link costs may change over time
  - Changes in traffic conditions
  - Link failures
  - Mobility
- Each node maintains its own routing table
  - Need to update table regularly to reflect changes in network
- Let $D_i$ be the shortest distance from node i to the destination
  - $D_i = \min\{j\} [D_j + d_{ij}]$ : update equation
- Each node (i) regularly updates the values of $D_i$ using the update equation
  - Each node maintains the values of $d_{ij}$ to its neighbors, as well as values of $D_j$ received from its neighbors
  - Uses those to compute $D_i$ and send new value of $D_i$ to its neighbors
  - If no changes occur in the network, algorithm will converge to shortest paths in no more than N steps

# Slow reaction to link failures



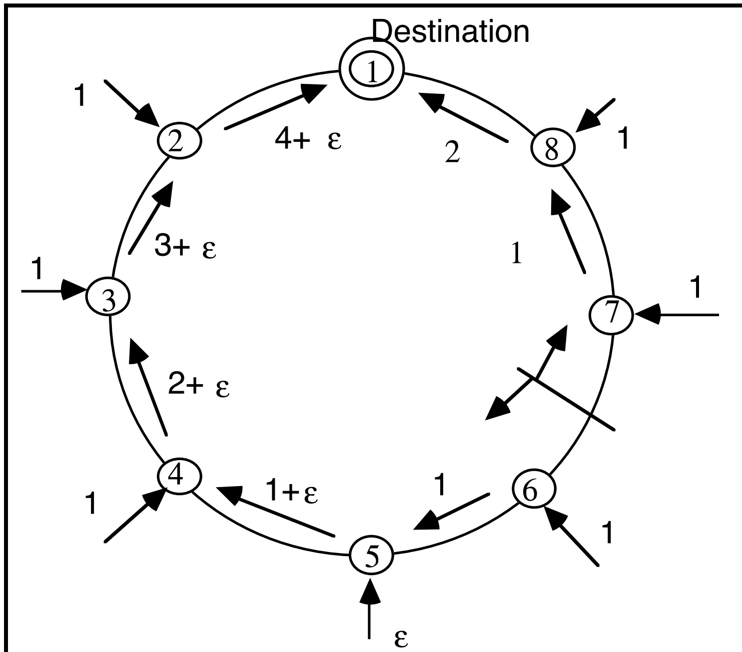

- Start with $D_3$=1 and $D_2$=100
  - After one iteration node 2 receives $D_3$=1 and $D_2$ = min [1+1, 100] = 2
- In practice, link lengths occasionally change
  - Suppose link between 3 and 1fails (i.e., $d_{31}$=infinity)
  - Node 3 will update $D_3 = d_{32} + D_2 = 3$
  - In the next step node 2 will update: $D_2 = d_{23}+D_3 = 4$
  - It will take nearly 100 iterations before node 2 converges on the correct route to node 1
- Possible solutions:
  - Propagate route information as well
  - Wait before rerouting along a path with increasing cost
    - Node next to failed link should announce D=infinity for some time to prevent loops

# Instability




**As routes change due to traffic conditions, they affect the Loadings on the links, hence routes may oscillate**

# Instability




Assume $d_{ij}$ is equal to the flow on (i,j) Note that $D_2$ now has a counter clockwise shortest path

- **Having a bias independent of flow in the arc distances helps to prevent this problem.**

- **Asynchronous updates also helps.**

# Dijkstra's algorithm

- **Find the shortest path from a given source node to all other nodes**
  - Requires non-negative arc weights

- **Algorithm works in stages:**

  - Stage k: the k closest nodes to the source have been found

  - Stage k+1: Given k closest nodes to the source node, find $k+1^{st}$

- **Key observation: the path to the $k+1^{st}$ closest nodes includes only nodes from among the k closest nodes**

- **Let M be the set of nodes already incorporated by the algorithm**
  - Start with $D_n = d_{sn}$ for all n ($D_n$ = shortest path distance from node n to the source node
  - Repeat until M = N

    Find node $w \notin M$ which has the next least cost distance to the source node
    Add w to M
    Update distances: $D_n = \min [ D_n, D_w + d_{wn}]$ (for all nodes $n \notin M$)

  - Notice that the update of $D_n$ need only be done for nodes not already in M and that the update only requires the computation of a new distance by going through the newly added node w

# Dijkstra example

# Dijkstra's algorithm implementation

- **Centralized version: Single node gets topology information and computes the routes**
  - **Routes can then be broadcast to the rest of the network**

- **Distributed version: each node i broadcasts {$d_{ij}$ all j} to all nodes of the network; all nodes can then calculate shortest paths to each other node**
  - **Open Shortest Path First (OSPF) protocol used in the internet**

# Routing in the Internet

- **Autonomous systems (AS)**
  - Internet is divided into AS's each under the control of a single authority
- **Routing protocol can be classified in two categories**
  - Interior protocols - operate within an AS
  - Exterior protocols - operate between AS's

- **Interior protocols**
  - Typically use shortest path algorithms
    - Distance vector - based on distributed Bellman-ford
    - link state protocols - Based on "distributed" Dijkstra's

# Distance vector protocols

- Based on distributed Bellman-Ford
  - Nodes exchange routing table information with their neighbors

- Examples:
  - Routing information protocols (RIP)

    Metric used is hop-count ($d_{ij}$=1)

    Routing information exchanged every 30 seconds

  - Interior Gateway Routing Protocol (IGRP)

    CISCO proprietary

    Metric takes load into account

    Dij ~ $1/(\mu-\lambda)$ (estimate delay through link)

    Update every 90 seconds

    Multi-path routing capability

# Link State Protocols

- Based on Dijkstra's Shortest path algorithm
  - Avoids loops
  - Routers monitor the state of their outgoing links
  - Routers broadcast the state of their links within the AS
  - Every node knows the status of all links and can calculate all routes using dijkstra's algorithm
    - Nonetheless, nodes only send packet to the next node along the route with the packets destination address. The next node will look-up the address in the routing table
- Example: Open Shortest Path First (OSPF) commonly used in the internet
- Link State protocols typically generate less "control" traffic than Distance-vector

# Inter-Domain routing

- Used to route packets across different AS's
- Options:
  - Static routing - manually configured routes
  - Distance-vector routing
    - Exterior Gateway Protocol (EGP)
    - Border Gateway Protocol (BGP)
- Issues
  - What cost "metric" to use for Distance-Vector routing
    - Policy issues: Network provider A may not want B's packets routed through its network or two network providers may have an agreement
    - Cost issues: Network providers may charge each other for delivery of packets

# Bridges, Routers and Gateways

- A Bridge is used to connect multiple LAN segments
  - Layer 2 routing (Ethernet)
  - Does not know IP address
  - Varying levels of sophistication
    - Simple bridges just forward packets
    - smart bridges start looking like routers
- A Router is used to route connect between different networks using network layer address
  - Within or between Autonomous Systems
  - Using same protocol (e.g., IP, ATM)
- A Gateway connects between networks using different protocols
  - Protocol conversion
  - Address resolution
- These definitions are often mixed and seem to evolve!

# Bridges, routers and gateways