Routing I: Basic Ideas

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Based in part upon slides of Prof. Raj Jain (OSU), S. Keshav (Cornell), J. Kurose (U Mass), Noel Chiappa (MIT)

- **Routing vs Forwarding**
- **Forwarding table vs Forwarding in simple topologies**
- **Routers vs Bridges: review**
- **Routing Problem**
- **Telephony vs Internet Routing**
- **Source-based vs Fully distributed Routing**
- **Distance vector vs Link state routing**
- **Addressing and Routing: Scalability**
- Refs: Chap 8, 11, 14, 16 in Comer textbook
- Books: “Routing in Internet” by Huitema, “Interconnections” by Perlman
- **Reading:** Notes for Protocol Design, E2e Principle, IP and Routing: In PDF
- **Reading:** Routing 101: Notes on Routing: In PDF | In MS Word
- **Reading:** Khanna and Zinky, The revised ARPANET routing metric
- Reference: Garcia-Luna-Aceves: "Loop-free Routing Using Diffusing Computations" :
- **Reading:** Alaettinoglu, Jacobson, Yu: "Towards Milli-Second IGP Convergence"

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Routing vs. Forwarding

- Forwarding: select an output port based on destination address and routing table
  - Data-plane function
  - Often implemented in hardware

- Routing: process by which routing table is *built..*
  - … so that the series of local forwarding decisions takes the packet to the destination with high probability, and …(reachability condition)
  - … the path chosen/resources consumed by the packet is *efficient* in some sense… (optimality and filtering condition)

  - Control-plane function
  - Implemented in software

Forwarding Table

- Can display forwarding table using "netstat -rn"
  - Sometimes called "routing table"

Destination	Gateway	Flags	Ref	Use	Interface
127.0.0.1	127.0.0.1	UH	0	26492	lo0
192.168.2.	192.168.2.5	U	2	13	fa0
193.55.114.	193.55.114.6	U	3	58503	le0
192.168.3.	192.168.3.5	U	2	25	qaa0
224.0.0.0	193.55.114.6	U	3	0	le0
default	193.55.114.129	UG	0	143454	

Forwarding Table *Structure*

- Fields: *destination, gateway, flags, ...*
- ***Destination***: can be a host address or a network address. If the 'H' flag is set, it is the host address.
- ***Gateway:*** router/next hop IP address. The 'G' flag says whether the destination is directly or indirectly connected.
- U flag: Is route up ?
- G flag: router (indirect vs direct)
- H flag: host (dest field: host or n/w address?)

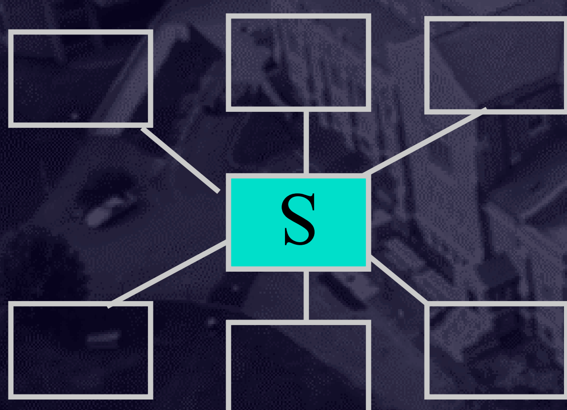
Key question:

- ***Why did we need this forwarding table in the first place ?***

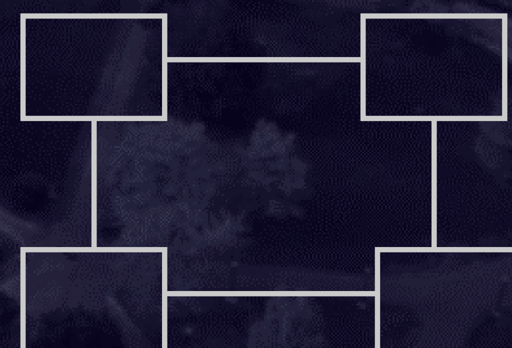
Routing in Simple Topologies

Bus: Drop pkt on the wire…

Full mesh: port# = dest-addr



Star: stubs point to hub; hub behaves like full mesh



Ring: send packet consistently in (anti-)clockwise direction

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Recall… Layer 1 & 2

- **Layer 1:**
  - *Hubs* do not have "forwarding tables" – they simply broadcast signals at Layer 1. No filtering.
- **Layer 2:**
  - Forwarding tables not required for simple topologies (previous slide): *simple forwarding rules suffice*
    - The next-hop could be *functionally* related to destination address (i.e. it can be computed without a table explicitly listing the mapping).
      - This places too many *restrictions* on topology and the assignment of addresses vis-à-vis ports at intermediate nodes.
    - Forwarding tables could be statically (*manually*) configured once or from time-to-time.
      - Does not accommodate *dynamism* in topology

Recall… Layer 2

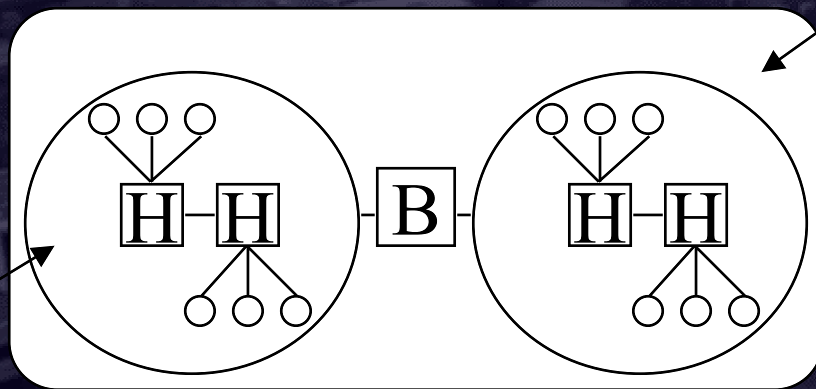
- Even reasonable sized LANs cannot tolerate above restrictions
- *Bridges* therefore have "*L2 forwarding tables*," and use dynamic learning algorithms to build it locally.
  - Even this allows LANs to scale, by limiting broadcasts and collisions to collision domains, and using bridges to interconnect collision domains.
  - The learning algorithm is purely local, opportunistic and expects no addressing structure.
  - Hence, bridges often may not have a forwarding entry for a destination address (I.e. *incomplete*)
  - In this case they resort to *flooding* – which may lead to duplicates of packets seen on the wire.
  - Bridges coordinate "globally" to build a spanning tree so that flooding doesn't go out of control.

Recall …: Layer 3

- *Routers* have "*L3 forwarding tables*," and use a distributed protocol to *coordinate* with other routers to *learn and condense a global view* of the network in a *consistent and complete* manner.
- Routers NEVER broadcast or flood if they don't have a route – they "pass the buck" to another router.
  - The good filtering in routers (I.e. restricting broadcast and flooding activity to be within broadcast domains) allows them to *interconnect broadcast domains*,
- Routers communicate with other routers, typically neighbors to collect an abstracted view of the network.
  - In the form of distance vector or link state.
  - Routers use algorithms like Dijkstra, Bellman-Ford to compute paths with such abstracted views.

Recall: Interconnection *Devices*

LAN= **Collision Domain**



Extended LAN =**Broadcast domain**

Router

Application	Gateway	Application
Transport		Transport
Network	Router	Network
Datalink	Bridge/Switch	Datalink
Physical	Repeater/Hub	Physical

Summary so far

- If *topology is simple and static, routing is simple* and may not even require a forwarding table
- If *topology is dynamic, but filtering requirements are weak* (I.e. network need not scale), then a local heuristic setup of forwarding table (bridging approach) suffices.
- Further, if a) filtering requirements are strict,
  b) optimal/efficient routing is desired, and
  c) we want small forwarding tables and bounded control traffic, then …

some kind of global communication, and smart distributed algorithms are needed to condense global state in a consistent, but yet complete way …

What's up in advanced routing?

- Routers are efficient in the collection of the abstracted view (control-plane filtering)
- Routers accommodate a variety of topologies, and sub-networks in an efficient manner
- Routers are organized in hierarchies to achieve scalability; and into autonomous systems to achieve complex policy-control over routing.
- Routers then condense paths into next hops, either:
  - depending upon other routers in a path to compute next-hops in a consistent manner (fully distributed), or
  - using a signaling protocol to enforce consistency.
- Advanced routing algorithms support "QoS routing" and "traffic engineering" goals like multi-path routing, source-based or distributed traffic splitting, fast re-route, path protection etc.

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Routing problem

- Collect, process, and condense global state into local forwarding information
- Global state
  - inherently large
  - dynamic
  - hard to collect
- *Hard issues:*
  - *consistency, completeness, scalability*
  - Impact of resource needs of sessions

Consistency

- Defn: A series of independent local forwarding decisions must lead to connectivity between any desired (source, destination) pair in the network.
- If the states are inconsistent, the network is said not to have "*converged*" to steady state (I.e. is in a transient state)
  - Inconsistency leads to *loops*, wandering packets etc
  - In general a part of the routing information may be consistent while the rest may be inconsistent.
  - Large networks => inconsistency is a scalability issue.
- Consistency can be achieved in two ways:
  - Fully distributed approach: a consistency criterion or invariant across the states of adjacent nodes
  - Signaled approach: the signaling protocol sets up local forwarding information along the path.

Completeness

- *Defn:* The network as a whole and every node has sufficient information to be able to compute all paths.
  - In general, with more complete information available locally, routing algorithms tend to converge faster, because the chances of inconsistency reduce.
  - But this means that more distributed state must be collected at each node and processed.
  - The demand for more completeness also limits the scalability of the algorithm.
- Since both consistency and completeness pose scalability problems, large networks have to be structured hierarchically and abstract entire networks as a single node.

Design Choices …

- *Centralized vs. distributed* routing
  - Centralized is simpler, but prone to failure and congestion
  - Centralized preferred in traffic engineering scenarios where complex optimization problems need to be solved and where routes chosen are long-lived
- *Source-based (explicit) vs. hop-by-hop (fully distributed)*
  - Will the source-based route be *signaled* to fix the path and to minimize packet header information?
    - Eg: ATM, Frame-relay etc
  - Or will the route be condensed and placed in each header? Eg: IP routing option
  - Intermediate: *loose source route*

Design choices…

- Static vs Dynamic Routing:
  - a) 'route' command [**Static**]
  - b) ICMP redirect message.[**Static**]
  - c) routing daemon.Eg: 'routed' [**Dynamic, connectionless**]
  - d) A signaling protocol [**Dynamic, virtual-circuit**]

Static vs Dynamic

Statically

Administrator manually configures forwarding table entries

+ More control
+ Not restricted to destination-based forwarding
- Doesn't scale
- Slow to adapt to network failures

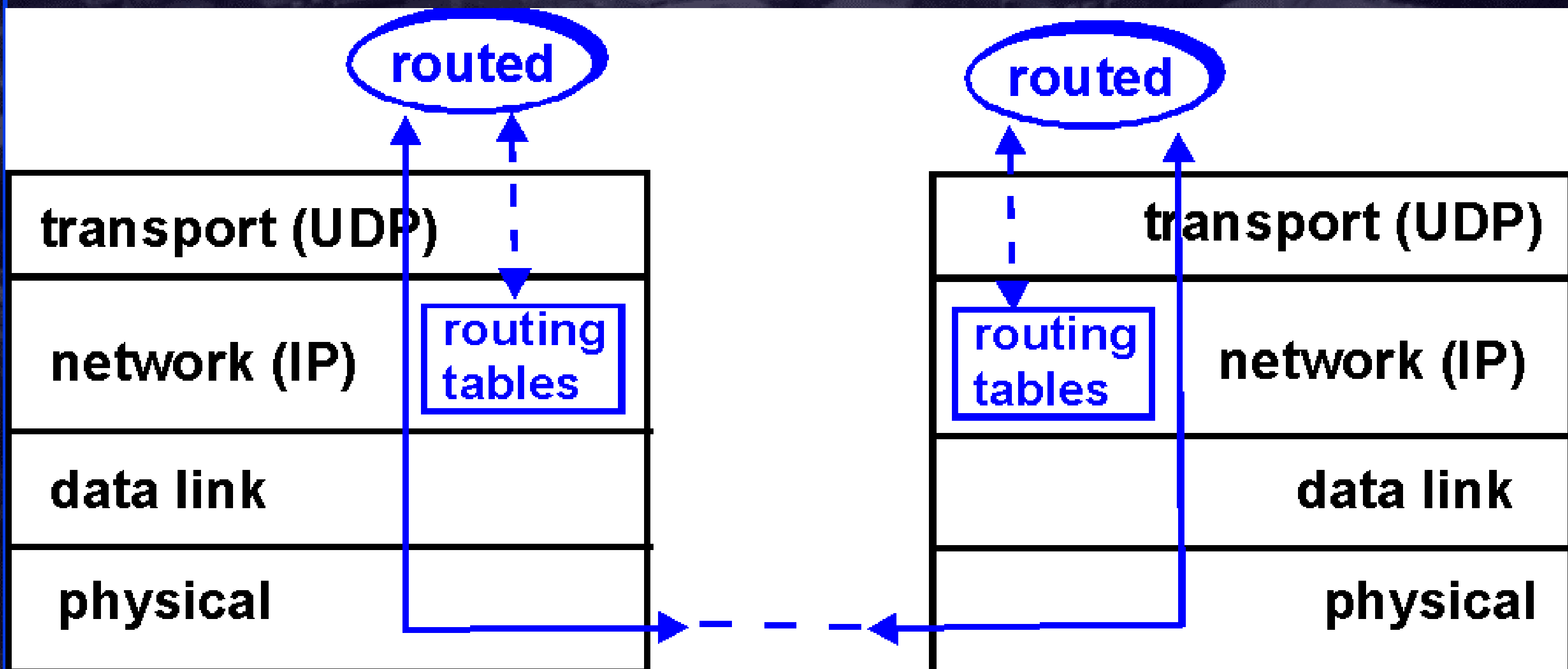
Dynamically

Routers exchange network reachability information using ROUTING PROTOCOLS. Routers use this to compute best routes

+ Can rapidly adapt to changes in network topology
+ Can be made to scale well
- Complex distributed algorithms
- Consume CPU, Bandwidth, Memory
- Debugging can be difficult
- Current protocols are destination-based

Practice : a mix of these.
Static routing mostly at the "edge"

Example Dynamic Routing Model



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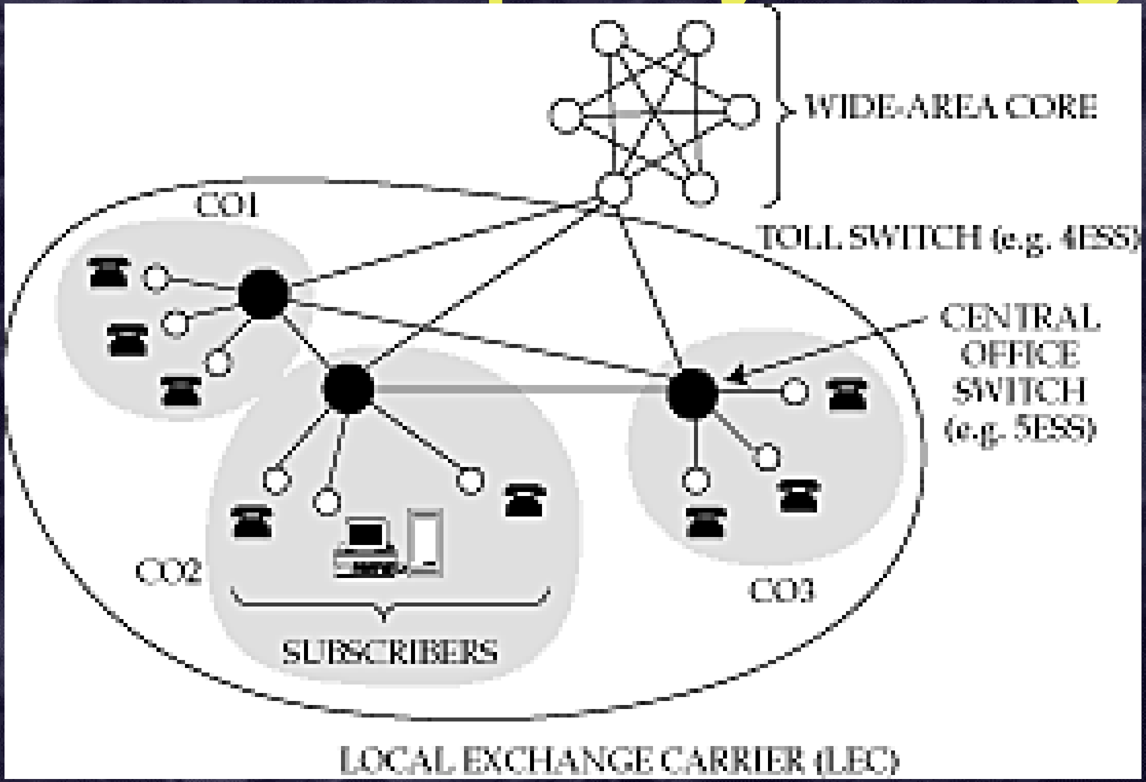
Detour: Telephony routing



- Circuit-setup is what is routed. Voice then follows route, and claims reserved resources.
- 3-level hierarchy, with a fully-connected core
- AT&T: 135 core switches with nearly 5 million circuits
- LECs may connect to multiple cores

Telephony Routing algorithm

- If endpoints are within same CO, directly connect
- If call is between COs in same LEC, use one-hop path between COs
- Otherwise send call to one of the cores
- Only major decision is at toll switch
  - one-hop or two-hop path to the destination toll switch.

- Essence of telephony routing problem:
  which *two-hop* path to use if *one-hop* path is full
  (almost a static routing problem…)

Features of telephone routing

- <u>Resource reservation aspects:</u>
  - Resource reservation is coupled with path reservation
    - Connections need resources (same 64kbps)
    - Signaling to reserve resources and the path
  - Stable load
    - Network built for voice only.
    - Can predict pairwise load throughout the day
    - Can choose optimal routes in advance
- <u>Technology and economic aspects:</u>
  - Extremely reliable switches
    - Why? End-systems (phones) dumb because computation was non-existent in early 1900s.
    - Downtime is less than a few minutes per year => topology does not change dynamically

Features of telephone routing

- Source can learn topology and compute route
- Can assume that a chosen route is available as the signaling proceeds through the network
- Component reliability drove system reliability and hence acceptance of service by customers

- Simplified topology:
  - Very highly connected network
  - Hierarchy + full mesh at each level: simple routing
  - High cost to achieve this degree of connectivity

- Organizational aspects:
  - Single organization controls entire core
  - Afford the scale economics to build expensive network
  - Collect global statistics and implement global changes

=> Source-based, signaled, simple alternate-path routing

Internet Routing Drivers

- Technology and economic aspects:
  - Internet built out of cheap, unreliable components as an overlay on top of leased telephone infrastructure for WAN transport.
    - Cheaper components => fail more often => topology changes often => needs dynamic routing
  - Components (including end-systems) had computation capabilities.
    - Distributed algorithms can be implemented
  - Cheap overlaid inter-networks => several entities could afford to leverage their existing (heterogeneous) LANs and leased lines to build inter-networks.
    - Led to multiple administrative "clouds" which needed to inter-connect for global communication.

Internet Routing Model

- 2 key features:
  - Dynamic routing
  - Intra- and Inter-AS routing, AS = locus of admin control
- Internet organized as *"autonomous systems" (AS).*
  - AS is internally connected
- Interior Gateway Protocols (IGPs) within AS.
  - Eg: RIP, OSPF, HELLO
- Exterior Gateway Protocols (EGPs) for AS to AS routing.
  - Eg: EGP, BGP-4

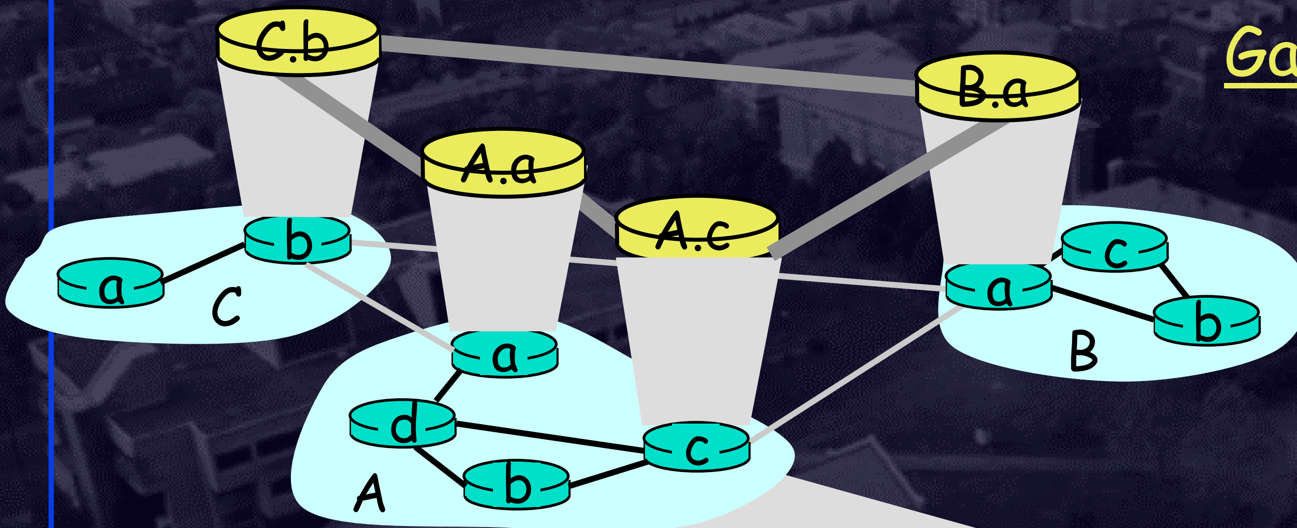
Requirements for Intra-AS Routing

- Should scale for the size of an AS.
  - Low end: 10s of routers (small enterprise)
  - High end: 1000s of routers (large ISP)
- Different requirements on routing convergence after topology changes
  - Low end: can tolerate some connectivity disruptions
  - High end: fast convergence essential to business (making money on transport)
- Operational/Admin/Management (OAM) Complexity
  - Low end: simple, self-configuring
  - High end: Self-configuring, but operator hooks for control
- Traffic engineering capabilities: high end only

Requirements for Inter-AS Routing

- Should <u>scale</u> for the size of the global Internet.
  - Focus on *reachability*, not optimality
  - Use *address aggregation* techniques to minimize core routing table sizes and associated control traffic
  - At the same time, it should allow *flexibility in topological structure* (eg: don't restrict to trees etc)
- Allow <u>policy-based routing</u> between autonomous systems
  - Policy refers to <u>*arbitrary preference among a menu of available options*</u> (based upon options' <u>*attributes*</u>)
  - In the case of routing, options include advertised AS-level routes to address prefixes
  - Fully distributed routing (as opposed to a signaled approach) is the only possibility.
  - Extensible to meet the demands for newer policies.

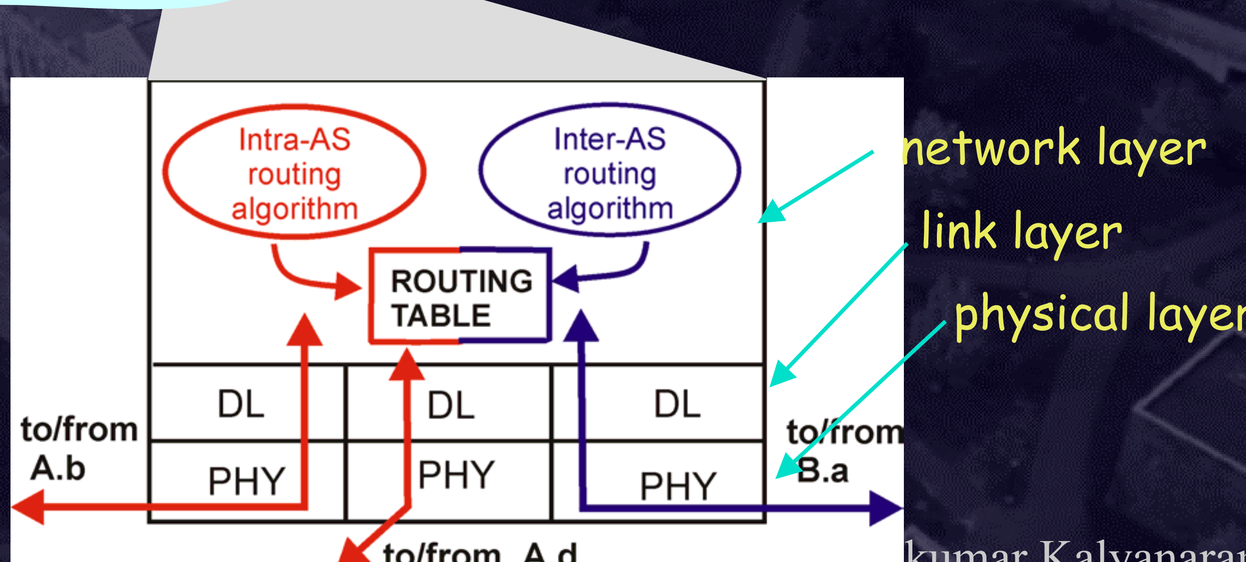
Intra-AS and Inter-AS routing



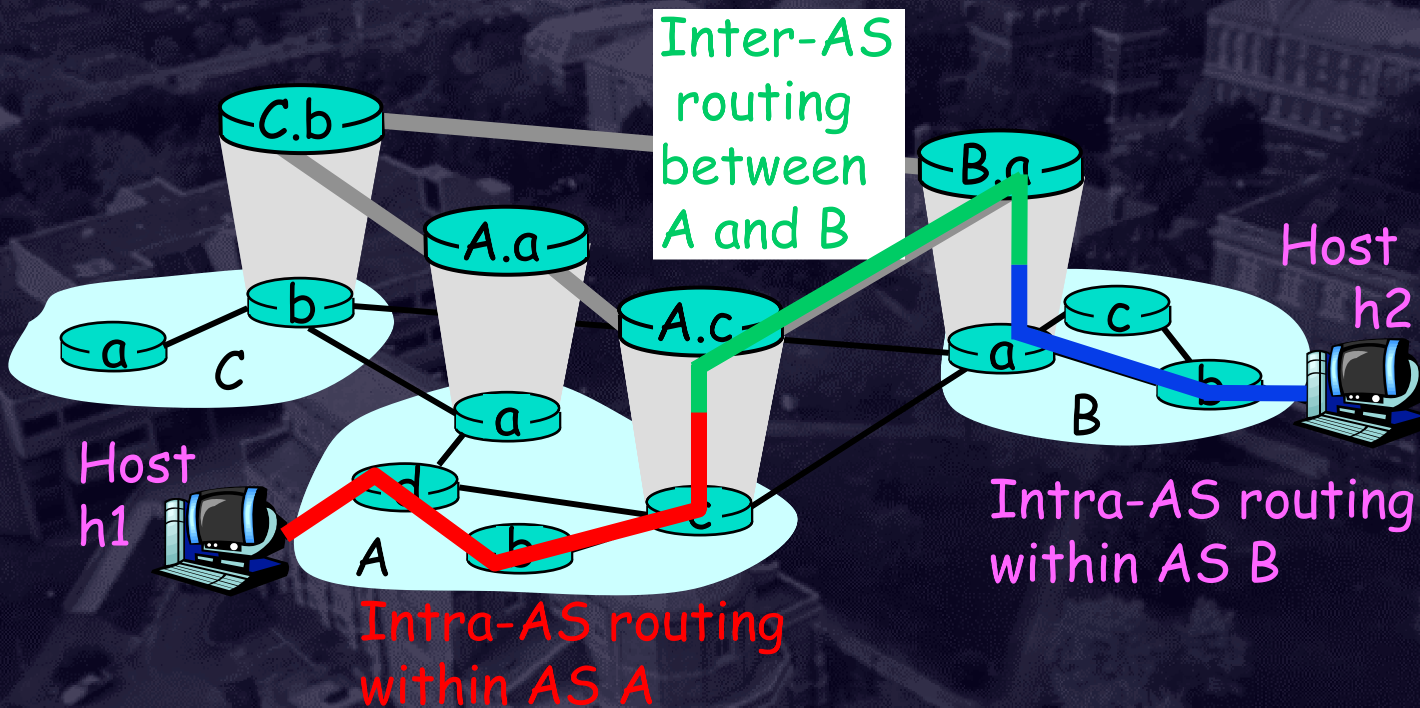
Gateways:

- perform inter-AS routing amongst themselves
- perform intra-AS routers with other routers in their AS

inter-AS, intra-AS routing in gateway A.c



Intra-AS and Inter-AS routing: Example



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Basic Dynamic Routing Methods

- Source-based: source gets a map of the network,
  - source finds route, and either
  - signals the route-setup (eg: ATM approach)
  - encodes the route into packets (inefficient)
- Link state routing: *per-link* information
  - Get *map* of network (in terms of *link states*) at all nodes and find next-hops locally.
  - Maps consistent => next-hops consistent
- Distance vector: *per-node* information
  - At every node, set up *distance signposts* to destination nodes (a vector)
  - Setup this by peeking at neighbors' signposts.

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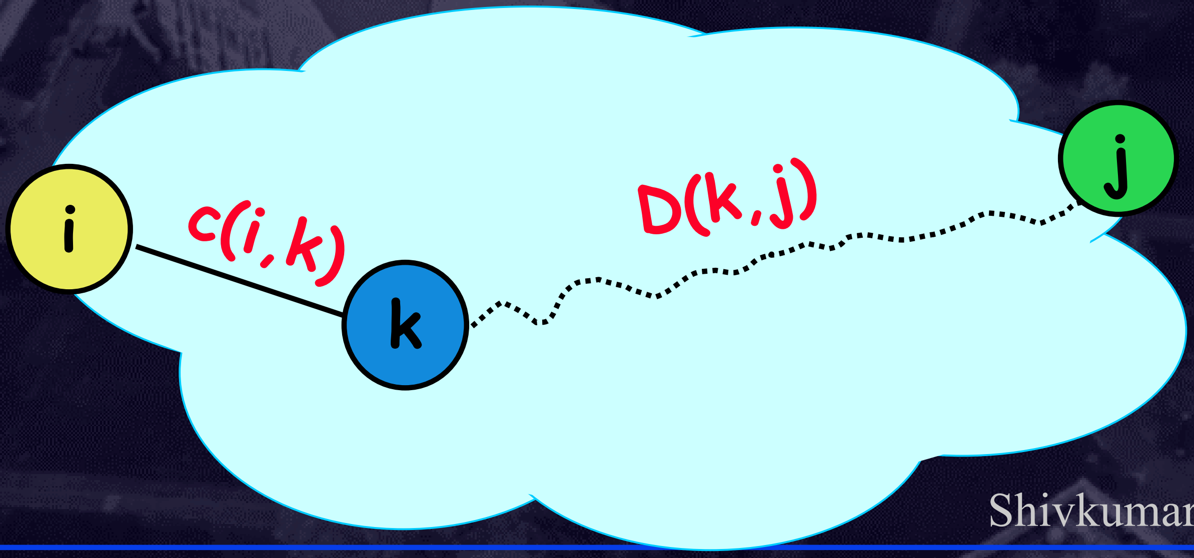
  - **Bellman Ford and Dijkstra Algorithms**
- Addressing and Routing: Scalability

DV & LS: consistency criterion

- *The subset of a shortest path is also the shortest path between the two intermediate nodes.*
- Corollary:
  - If the shortest path from node i to node j, with distance D(i,j) passes through neighbor k, with link cost c(i,k), then:

$$D(i,j) = c(i,k) + D(k,j)$$



Distance Vector

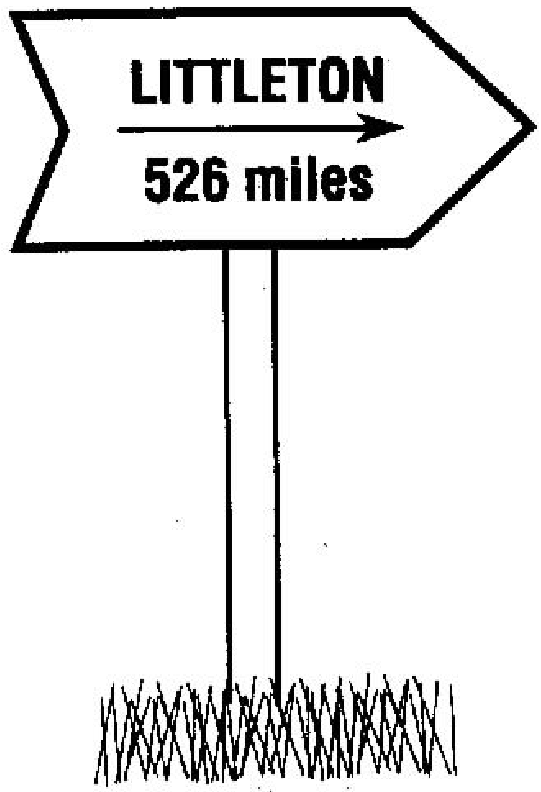


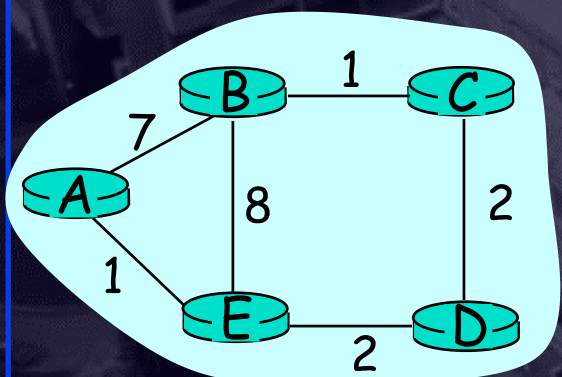
Figure 12.2 Sign points the way, gives distance

DV = Set (vector) of Signposts, one for each destination

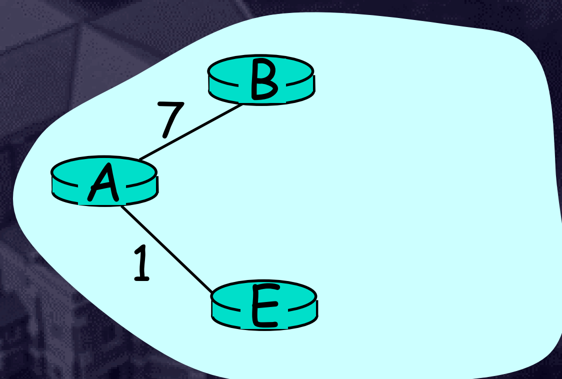
Distance Vector (DV) Approach

<u>Consistency Condition:</u> **D(i,j) = c(i,k) + D(k,j)**

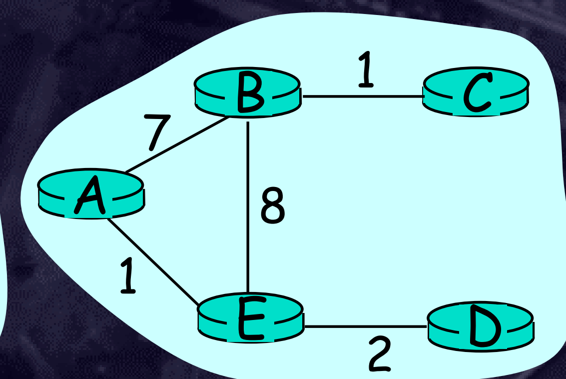
- The *DV (Bellman-Ford) algorithm* evaluates this recursion <u>iteratively</u>.
  - In the <u>m^th iteration</u>, the consistency criterion holds, assuming that each node sees all nodes and links m-hops (or smaller) away from it (i.e. an <u>m-hop view</u>)



Example network



A's 1-hop view (After 1st iteration)



A's 2-hop view (After 2nd Iteration)

Distance Vector (DV)…

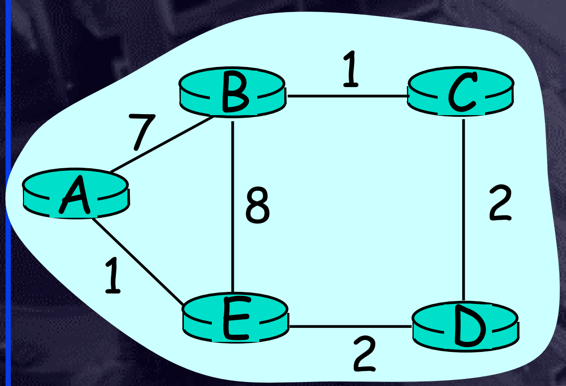
- Initial distance values (iteration 1):
  - **D(i,i) = 0 ;**
  - **D(i,k) = c(i,k)** if k is a neighbor (i.e. k is one-hop away); and
  - **D(i,j) = INFINITY** for all other non-neighbors j.
- Note that the set of values **D(i,*)** is a distance vector at node i.
- The algorithm also maintains a next-hop value (forwarding table) for every destination j, initialized as:
  - **next-hop(i) = i;**
  - **next-hop(k) = k** if k is a neighbor, and
  - **next-hop(j) = UNKNOWN** if j is a non-neighbor.

Distance Vector (DV).. (Cont'd)

- After every iteration each node i exchanges its distance vectors D(i,*) with its immediate neighbors.
- For any neighbor k, if **c(i,k) + D(k,j) < D(i,j),** then:
  - **D(i,j) = c(i,k) + D(k,j)**
  - **next-hop(j) = k**
- After each iteration, the consistency criterion is met
  - After *m* iterations, each node knows the shortest path possible to any other node which is *m* hops or less.
  - I.e. each node has an m-hop view of the network.
  - The algorithm converges (self-terminating) in O(d) iterations: d is the maximum diameter of the network.

Distance Vector (DV) Example

- A's distance vector D(A,*):
  - After Iteration 1 is: [0, 7, INFINITY, INFINITY, 1]
  - After Iteration 2 is: [0, 7, 8, 3, 1]
  - After Iteration 3 is: [0, 7, 5, 3, 1]
  - After Iteration 4 is: [0, 6, 5, 3, 1]



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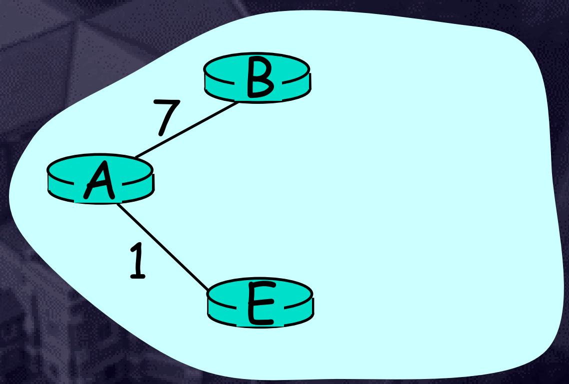
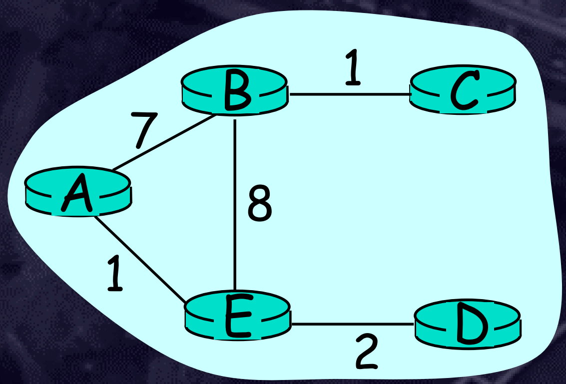


A's 1-hop view (After 1st iteration)

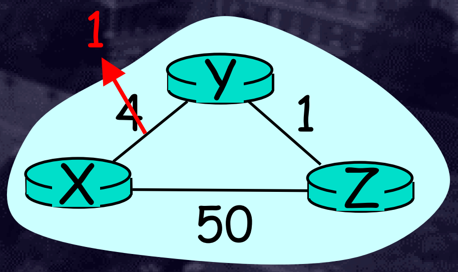


A's 2-hop view (After 2nd Iteration)

Distance Vector: *link cost changes*

Link cost changes:

- node detects local link cost change
- updates distance table
- if cost change in least cost path, notify neighbors



"good news travels fast"

	Time 0	Iter. 1	Iter. 2
DV(Y)	[4 0 1]	[1 0 1]	[1 0 1]
DV(Z)	[5 1 0]	[5 1 0]	[2 1 0]

algorithm terminates

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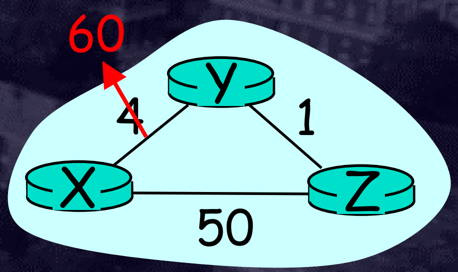
Distance Vector: *link cost changes*

Link cost changes:

- good news travels fast
- bad news travels slow - "count to infinity" problem!



	Time 0	Iter 1	Iter 2	Iter 3	Iter 4
DV(Y)	[4 0 1]	[6 0 1]	[6 0 1]	[8 0 1]	[8 0 1]
DV(Z)	[5 1 0]	[5 1 0]	[7 1 0]	[7 1 0]	[9 1 0]

algo goes on!

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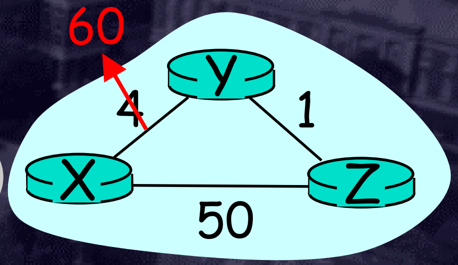
Distance Vector: *poisoned reverse*

- If Z routes through Y to get to X :
  - Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z)
  - At Time 0, DV(Z) *as seen by Y* is **[INF INF 0]**, *not* **[5 1 0]** !

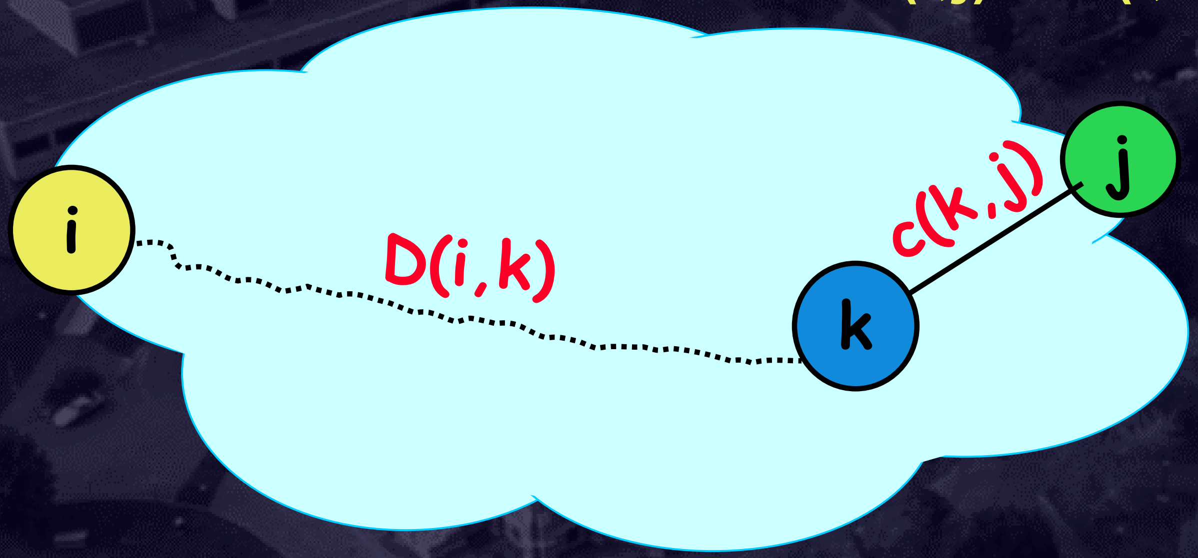


	Time 0	Iter 1	Iter 2	Iter 3
DV(Y)	[4 0 1]	[60 0 1]	[60 0 1]	[51 0 1]
DV(Z)	[5 1 0]	[5 1 0]	[50 1 0]	[7 1 0]

algorithm terminates

Link State (LS) Approach

- The *link state (Dijkstra) approach is iterative, but it* pivots around destinations j, and their predecessors k = p(j)
  - Observe that an alternative version of the consistency condition holds for this case: **D(i,j) = D(i,k) + c(k,j)**



- Each node i collects all link states **c(*,*)** first and runs the complete Dijkstra algorithm locally.

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Link State (LS) Approach…

- After each iteration, the algorithm finds a new destination node j and a shortest path to it.
- After m iterations the algorithm has explored paths, which are m hops or smaller from node i.
  - It has an m-hop view of the network just like the distance-vector approach
- The Dijkstra algorithm at node i maintains two sets:
  - **set N** that contains nodes to which the shortest paths have been found so far, and
  - **set M** that contains all <u>other</u> nodes.
  - For all nodes k, two values are maintained:
    - **D(i,k):** current value of <u>distance</u> from i to k.
    - **p(k):** the <u>predecessor</u> node to k on the shortest known path from i

Dijkstra: Initialization

- **Initialization:**
  - **D(i,i) = 0   and   p(i) = i;**
  - **D(i,k) = c(i,k)   and   p(k) = i** if k is a neighbor of I
  - **D(i,k) = INFINITY   and   p(k) = UNKNOWN** if k is *not* a neighbor of I
  - **Set N = { i },** and **next-hop (i) = I**
  - **Set M = { j | j is not i}**
- Initially set N has only the node i and set M has the rest of the nodes.
- At the end of the algorithm, the set N contains all the nodes, and set M is empty

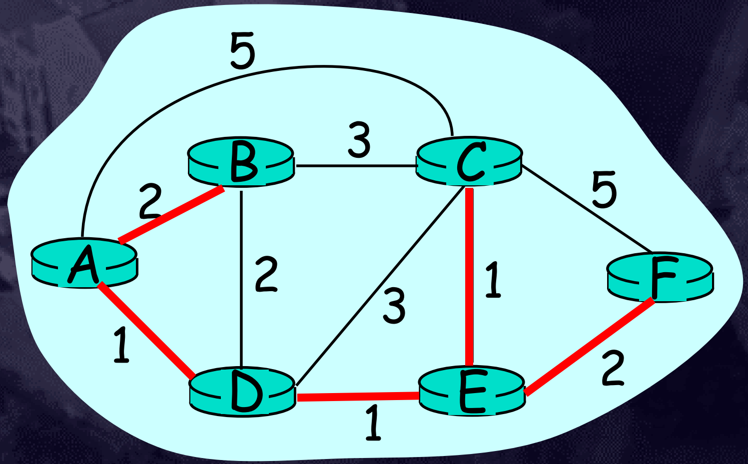
Dijkstra: Iteration

- In each iteration, a new node j is moved from set M into the set N.
  - Node j has the minimum distance among all current nodes in M, i.e. **$D(i,j) = \min_{\{l \in M\}} D(i,l)$.**
  - If multiple nodes have the same minimum distance, any one of them is chosen as j.
  - **Next-hop(j) =** the neighbor of i on the shortest path
    - **Next-hop(j) = next-hop(p(j))** **if p(j) is not i**
    - **Next-hop(j) = j** **if p(j) = i**
  - Now, in addition, the distance values of any neighbor k of j in set M is reset as:
    - **If D(i,k) < D(i,j) + c(j,k), then**

    D(i,k) = D(i,j) + c(j,k), and p(k) = j.
- This operation is called "*relaxing*" the edges of node j.

Dijkstra's algorithm: *example*

Step	set N	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					

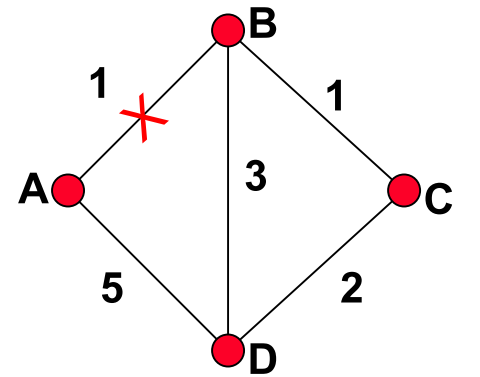


The shortest-paths spanning tree rooted at A is called an SPF-tree

Shivkumar Kalyanaraman

Miscl Issues: Transient Loops

- With consistent LSDBs, all nodes compute consistent loop-free paths
- Limited by Dijkstra computation overhead, space requirements
- Can still have *transient loops*



Packet from C→A may loop around BDC if B knows about failure and C & D do not

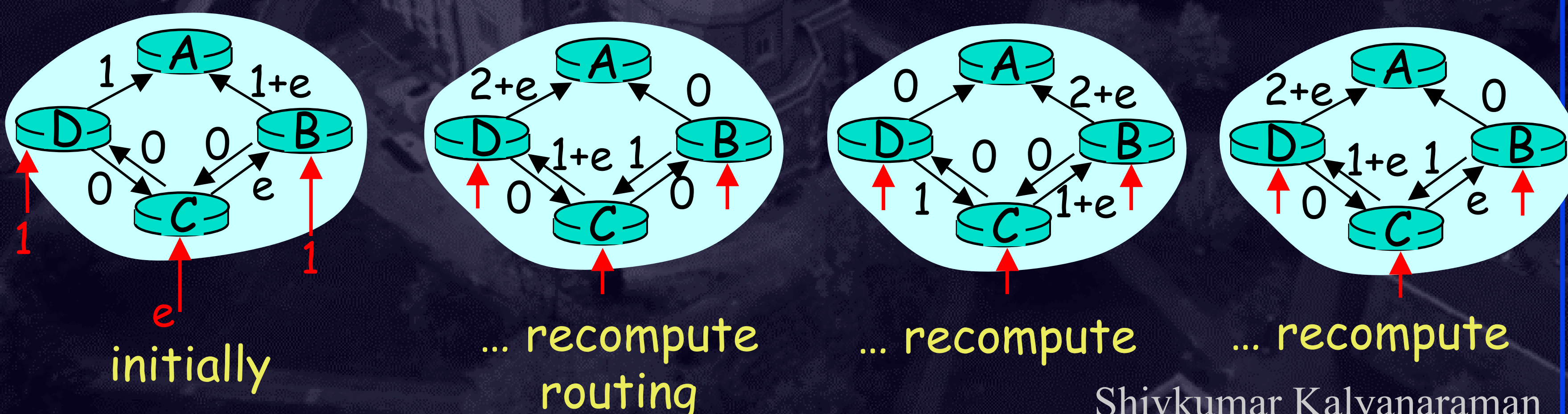
Dijkstra's algorithm, discussion

Algorithm complexity: n nodes

- each iteration: need to check all nodes, w, not in N
- n*(n+1)/2 comparisons: O(n**2)
- more efficient implementations possible: O(nlogn)

Oscillations possible:

- e.g., link cost = amount of carried traffic



Misc: How to assign the Cost Metric?

- Choice of link cost defines traffic load
  - Low cost = high probability link belongs to SPT and will attract traffic
- Tradeoff: convergence vs load distribution
  - Avoid oscillations
  - Achieve good network utilization
- **Static metrics** (weighted hop count)
  - Does not take traffic load (demand) into account.
- **Dynamic metrics** (cost based upon queue or delay etc)
  - Highly oscillatory, very hard to dampen (DARPAnet experience)
- **Quasi-static metric**:
  - Reassign static metrics based upon overall network load (demand matrix), assumed to be quasi-stationary

Misc: Incremental SPF Algorithms

- Dijkstra algorithm is invoked whenever a new LS update is received.
  - Most of the time, the change to the SPT is minimal, or even nothing
- If the node has visibility to a large number of prefixes, then it may see large number of updates.
- Flooding bugs further exacerbate the problem
- Solution: incremental SPF algorithms which use knowledge of current map and SPT, and process the delta change with lower computational complexity compared to Dijkstra
  - Avg case: O(logn) compared to O(nlogn) for Dijkstra
- Ref: Alaettinoglu, Jacobson, Yu, "Towards Milli-Second IGP Convergence," Internet Draft.

Summary: Distributed Routing Techniques

Link State

- Topology information is flooded within the routing domain
- Best end-to-end paths are computed locally at each router.
- Best end-to-end paths determine next-hops.
- Based on minimizing some notion of distance
- Works only if policy is shared and uniform
- Examples: OSPF, IS-IS

Vectoring

- Each router knows little about network topology
- Only best next-hops are chosen by each router for each destination network.
- Best end-to-end paths result from composition of all next-hop choices
- Does not require any notion of distance
- Does not require uniform policies at all routers
- Examples: RIP, BGP

Where are we?

- Routing vs Forwarding
- Forwarding table vs Forwarding in simple topologies
- Routers vs Bridges: review
- Routing Problem
- Telephony vs Internet Routing
- Source-based vs Fully distributed Routing
- Distance vector vs Link state routing
  - Bellman Ford and Dijkstra Algorithms

- **Addressing and Routing: Scalability**

Addressing: Objects

- Address is a numerical "name" which refers to an **object**
- There are several types of objects we'd like to refer to at the network layer…
- **Interface:**
  - A place to which a producer or consumer of packets connects to the network; a *network attachment point*
- **Network:**
  - A collection of interfaces which have some useful relationship:
  - Any interface can send directly to any other without going through a router
  - A topology aggregate

Addressing: Objects

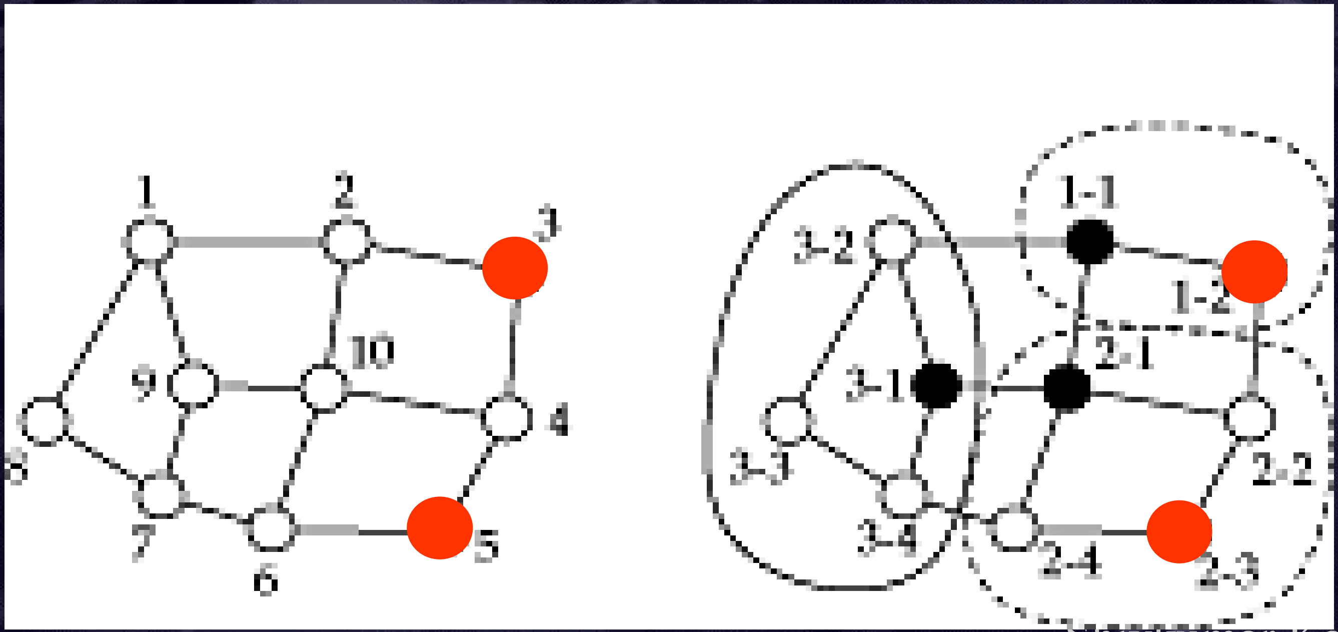
- **Route or Path:**
  - A path from one place in the network to another
- **Host:**
  - An actual machine which is the source or destination of traffic, through some interface
- **Router:**
  - A device which is interconnecting various elements of the network, and forwarding traffic
- **Node:**
  - A host or router

Address Concept

- **Address:** A structured name for a network interface or topology aggregate:
- The structure is used by the routing to help it scale
- Topologically related items **have** to be given **related** addresses
- Topologically related addresses also:
  - Allow the number of *destinations* tracked by the routing to be minimized
  - Allow quick location of the named interface on a map
  - Provide a representation for topology distribution
  - Provide a framework for the abstraction process
- DNS names:
  - A structured human usable name for a host, etc
  - The structure facilitates the distribution and lookup

Flat vs Structured Addresses

- **Flat addresses:** no structure in them to facilitate scalable routing
  - Eg: IEEE 802 LAN addresses
- **Hierarchical addresses:**
  - Network part (prefix) and host part
  - Helps identify direct or indirectly connected nodes



Tradeoffs in Large Scale Routing

- Tradeoff: discard detailed routing information vs incur the overhead of large, potentially unneeded detail.
  - This process is called *abstraction*.
- There are two types of abstraction for routing:
  - *Compression*, in which the same routing decision is made in all cases after the abstraction as before
  - *Thinning*, in which the routing is affected
  - If the prior routing was optimal, discarding routing information via thinning means non-optimal routes
- Large-scale routing incurs two kinds of overhead cost:
  - The cost of running the routing
  - The cost of non-optimal routes
  - Challenge of routing is managing this choice of costs.

Hierarchical Routing Example: PNNI

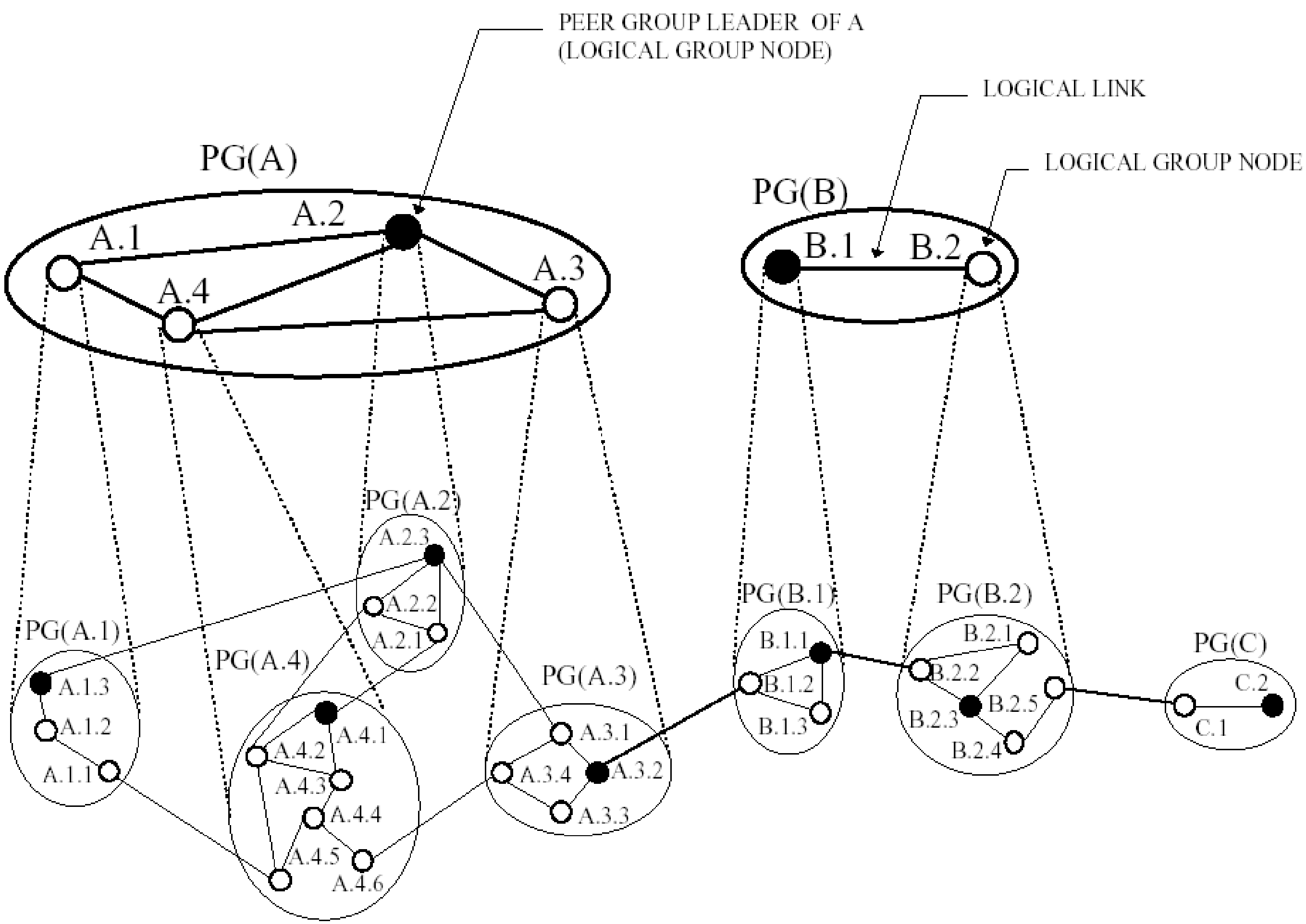


Figure 3-3: Partially configured PNNI hierarchy showing lowest hierarchical levels.

Summary

- Routing Concepts
- DV and LS algorithms
- Addressing and Hierarchy