Introduction to Computer Networks

Routing Overview

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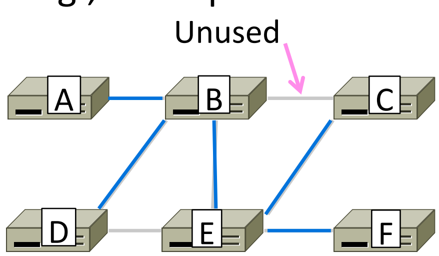
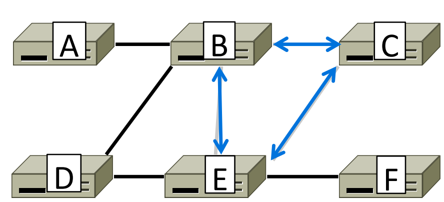
Improving on the Spanning Tree

- Spanning tree provides basic connectivity
  - e.g., some path B→C



- Routing uses all links to find "best" paths
  - e.g., use BC, BE, and CE



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Perspective on Bandwidth Allocation

- Routing allocates network bandwidth adapting to failures; other mechanisms used at other timescales

Mechanism	Timescale / Adaptation
Load-sensitive routing	Seconds / Traffic hotspots
Routing	Minutes / Equipment failures
Traffic Engineering	Hours / Network load
Provisioning	Months / Network customers

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Goals of Routing Algorithms

- What are the properties we want of any routing scheme?

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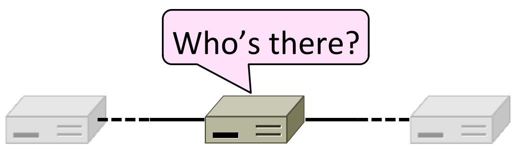
Rules of Routing Algorithms

- Decentralized, distributed setting
  - All nodes are alike; no controller
  - Nodes only know what they learn by exchanging messages with neighbors
  - Nodes operate concurrently
  - May be node/link/message failures



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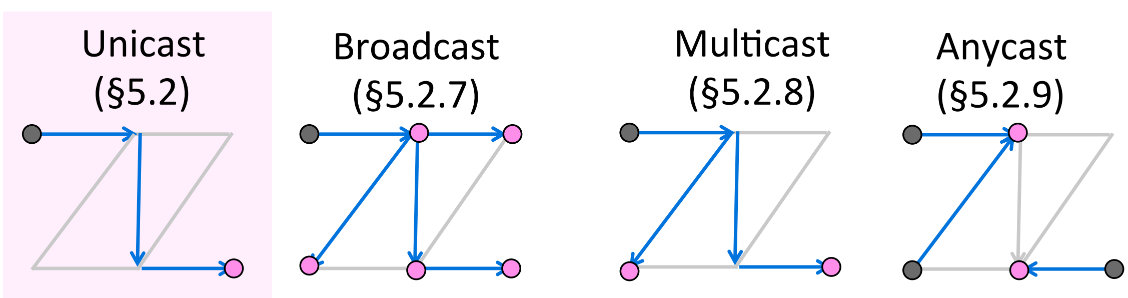
Delivery Models

- Different routing used for different delivery models



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Shortest Path Routing

(§5.2.1-5.2.2)

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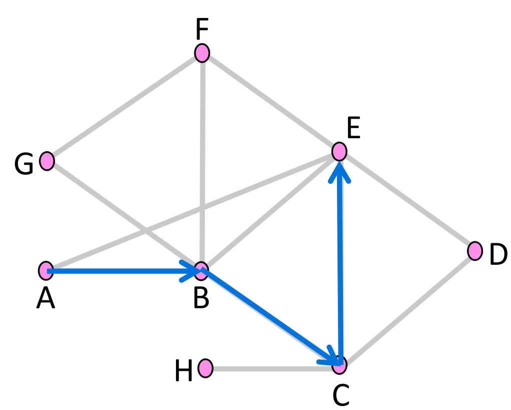
What are "Best" paths anyhow?

- Many possibilities:
  - Latency, avoid circuitous paths
  - Bandwidth, avoid slow links
  - Money, avoid expensive links
  - Hops, to reduce switching
- But only consider topology
  - Ignore workload, e.g., hotspots



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Shortest Paths

We'll approximate "best" by a cost function that captures the factors

– Often call lowest "shortest"

1. Assign each link a cost (distance)
2. Define best path between each pair of nodes as the path that has the lowest total cost (or is shortest)
3. Pick randomly to break ties

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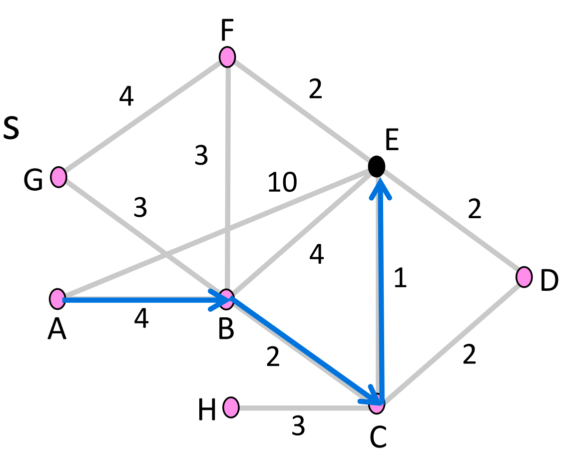
Sink Trees

- Sink tree for a destination is the union of all shortest paths towards the destination
  – Similarly source tree



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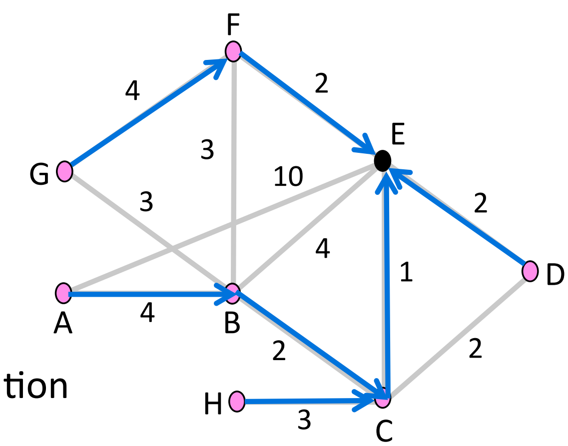
Sink Trees (2)

- Implications:
  - Only need to use destination to follow shortest paths
  - Each node only need to send to the next hop
- Forwarding table at a node
  - Lists next hop for each destination
  - Routing table may know more



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Dijkstra's Algorithm

Algorithm:

- Mark all nodes tentative, set distances from source to 0 (zero) for source, and ∞ (infinity) for all other nodes
- While tentative nodes remain:
  - Extract N, the one with lowest distance
  - Add link to N to the shortest path tree
  - Relax the distances of neighbors of N by lowering any better distance estimates

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Dijkstra Comments

- Dynamic programming algorithm; leverages optimality property
- Runtime depends on efficiency of extracting min-cost node
- Gives us complete information on the shortest paths to/from one node
  - But requires complete topology

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Distance Vector Routing
(§5.2.4)

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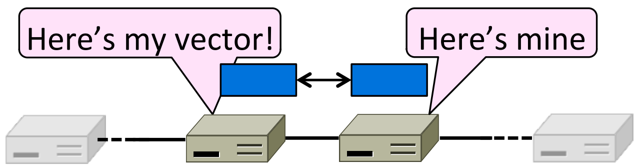
Topic

- How to compute shortest paths in a distributed network
  - The Distance Vector (DV) approach



Distance Vector Routing

- Simple, early routing approach
  - Used in ARPANET, and "RIP"
- One of two main approaches to routing
  - Distributed version of Bellman-Ford
  - Works, but very slow convergence after some failures
- Link-state algorithms are now typically used in practice
  - More involved, better behavior

Distance Vector Setting

Each node computes its forwarding table in a distributed setting:

1. Nodes know only the cost to their neighbors; not the topology
2. Nodes can talk only to their neighbors using messages
3. All nodes run the same algorithm concurrently
4. Nodes and links may fail, messages may be lost

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Distance Vector Algorithm

Each node maintains a vector of distances to all destinations

1. Initialize vector with 0 (zero) cost to self, ∞ (infinity) to other destinations
2. Periodically send vector to neighbors
3. Update vector for each destination by selecting the shortest distance heard, after adding cost of neighbor link
   - Use the best neighbor for forwarding

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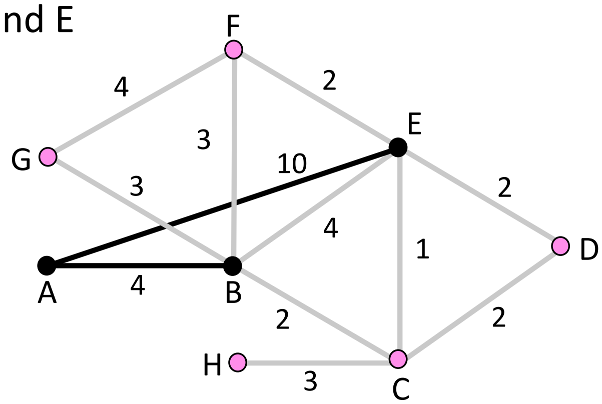
Distance Vector (2)

- Consider from the point of view of node A
  - Can only talk to nodes B and E

Initial vector

To	Cost
A	0
B	∞
C	∞
D	∞
E	∞
F	∞
G	∞
H	∞



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Distance Vector (3)

- First exchange with B, E; learn best 1-hop routes

To	B says	E says
A	∞	∞
B	0	∞
C	∞	∞
D	∞	∞
E	∞	0
F	∞	∞
G	∞	∞
H	∞	∞

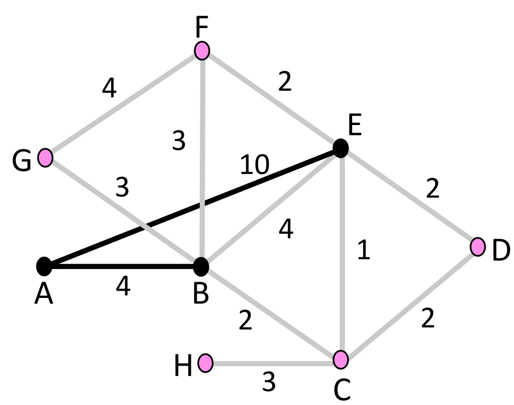
→

B +4	E +10
∞	∞
4	∞
∞	∞
∞	∞
∞	10
∞	∞
∞	∞
∞	∞

→

A's Cost	A's Next
0	--
4	B
∞	--
∞	--
10	E
∞	--
∞	--
∞	--

Learned better route



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Distance Vector (4)

- Second exchange; learn best 2-hop routes

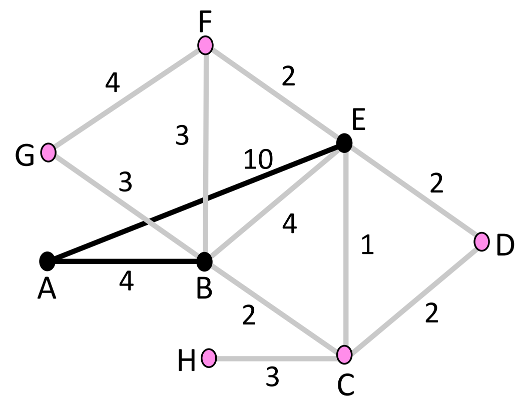
To	B says	E says
A	4	10
B	0	4
C	2	1
D	∞	2
E	4	0
F	3	2
G	3	∞
H	∞	∞

→

B +4	E +10
8	20
4	14
6	11
∞	12
8	10
7	12
7	∞
∞	∞

→

A's Cost	A's Next
0	--
4	B
6	B
12	E
8	B
7	B
7	B
∞	--



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Distance Vector (4)

- Third exchange; learn best 3-hop routes

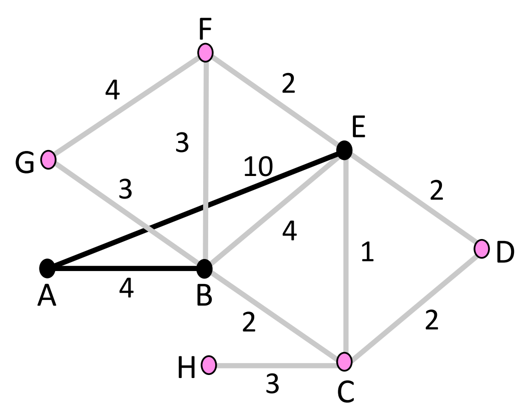
To	B says	E says
A	4	8
B	0	3
C	2	1
D	4	2
E	3	0
F	3	2
G	3	6
H	5	4

→

B +4	E +10
8	18
4	13
6	11
8	12
7	10
7	12
7	16
9	14

→

A's Cost	A's Next
0	--
4	B
6	B
8	B
7	B
7	B
7	B
9	B



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Distance Vector (5)

- Subsequent exchanges; converged

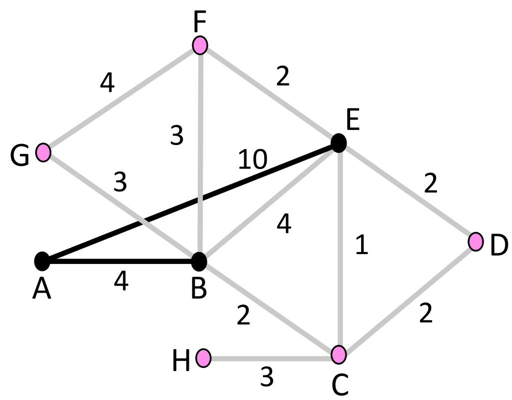
To	B says	E says
A	4	7
B	0	3
C	2	1
D	4	2
E	3	0
F	3	2
G	3	6
H	5	4

→

B +4	E +10
8	17
4	13
6	11
8	12
7	10
7	12
7	16
9	14

→

A's Cost	A's Next
0	--
4	B
6	B
8	B
8	B
7	B
7	B
9	B



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Distance Vector Dynamics

- Adding routes:
  - News travels one hop per exchange
- Removing routes
  - When a node fails, no more exchanges, other nodes forget
- But <u>partitions</u> (unreachable nodes in divided network) are a problem
  - "Count to infinity" scenario

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Dynamics (2)

- Good news travels quickly, bad news slowly (inferred)

A	B	C	D	E	
	•	•	•	•	Initially
	1	•	•	•	After 1 exchange
	1	2	•	•	After 2 exchanges
	1	2	3	•	After 3 exchanges
	1	2	3	4	After 4 exchanges

Desired convergence

A	X	B	C	D	E	
		1	2	3	4	Initially
		3	2	3	4	After 1 exchange
		3	4	3	4	After 2 exchanges
		5	4	5	4	After 3 exchanges
		5	6	5	6	After 4 exchanges
		7	6	7	6	After 5 exchanges
		7	8	7	8	After 6 exchanges
			⋮			

"Count to infinity" scenario

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Dynamics (3)

- Various heuristics to address
  - e.g.,"Split horizon, poison reverse" (Don't send route back to where you learned it from.)
- But none are very effective
  - Link state now favored in practice
  - Except when very resource-limited

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Introduction to Computer Networks

Link State Routing (§5.2.5)

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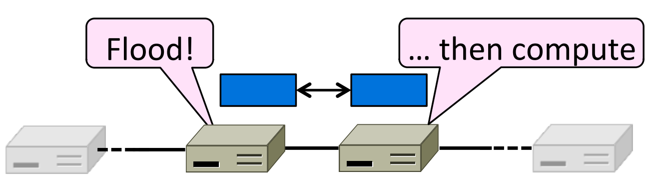
Topic

- How to compute shortest paths in a distributed network
  - The Link-State (LS) approach



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Link-State Routing

- One of two approaches to routing
  - Trades more computation than distance vector for better dynamics
- Widely used in practice
  - Used in Internet/ARPANET from 1979
  - Modern networks use OSPF and IS-IS

Link-State Algorithm

Proceeds in two phases:

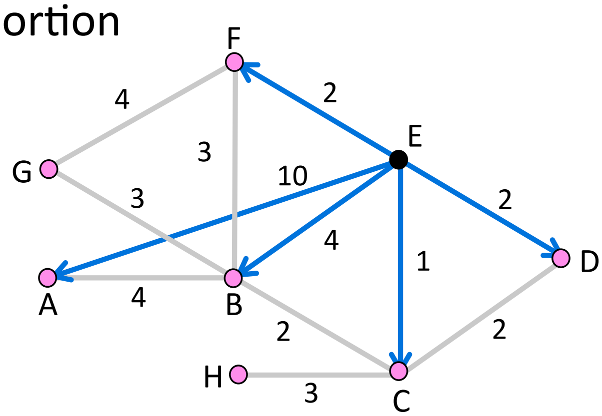
1. Nodes flood topology in the form of link state packets
   - Each node learns full topology
2. Each node computes its own forwarding table
   - By running Dijkstra (or equivalent)

Topology Dissemination

- Each node floods link state packet (LSP) that describes their portion of the topology

Node E's LSP flooded to A, B, C, D, and F

Seq. #	
A	10
B	4
C	1
D	2
F	2



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Route Computation

- Each node has full topology
  - By combining all LSPs
- Each node simply runs Dijkstra
  - Some replicated computation, but finds required routes directly
  - Compile forwarding table from sink/ source tree
  - That's it folks!

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Handling Changes

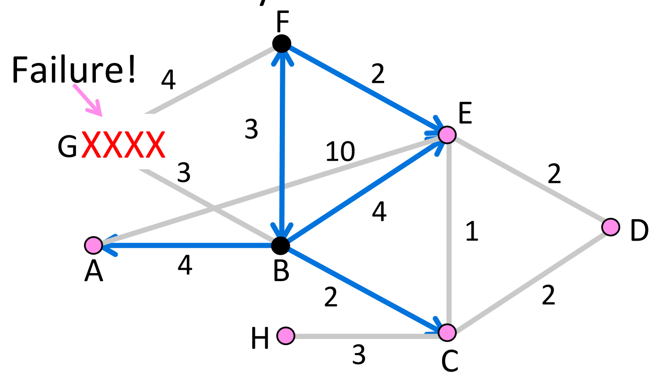
- Nodes adjacent to failed link or node will notice
  - Flood updated LSP with less connectivity

B's LSP

Seq. #	
A	4
C	2
E	4
F	3
~~G~~	~~3~~

F's LSP

Seq. #	
B	3
E	2
~~G~~	~~4~~



Handling Changes (2)

- Link failure
  - Both nodes notice, send updated LSPs
  - Link is removed from topology
- Node failure
  - All neighbors notice a link has failed
  - Failed node can't update its own LSP
  - But it is OK: all links to node removed

Handling Changes (3)

- Addition of a link or node
  - Add LSP of new node to topology
  - Old LSPs are updated with new link
- Additions are the easy case …

Link State Complications

- What can go wrong?

DV/LS Comparison

- How do the two compare?

Introduction to Computer Networks

Equal-Cost Multi-Path Routing
(§5.2.1)

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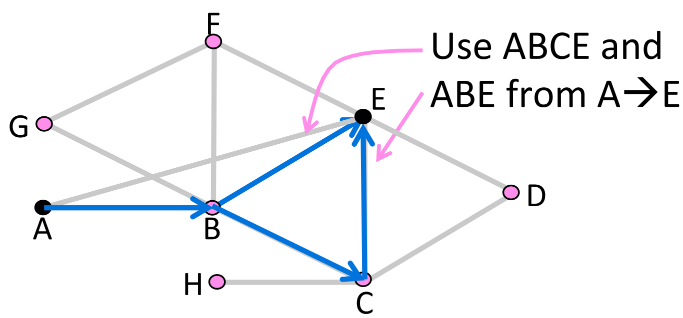
Topic

- More on shortest path routes
  - Allow multiple shortest paths



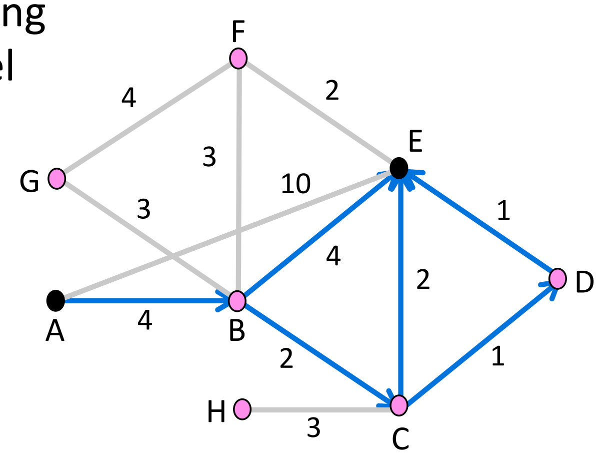
Multipath Routing

- Allow multiple routing paths from node to destination be used at once
  - Topology has them for redundancy
  - Using them can improve performance
- Questions:
  - How do we find multiple paths?
  - How do we send traffic along them?

Equal-Cost Multipath Routes

- One form of multipath routing
- Extends shortest path model
  - Keep set if there are ties

- Consider A→E
  - ABE = 4 + 4 = 8
  - ABCE = 4 + 2 + 2 = 8
  - ABCDE = 4 + 2 + 1 + 1 = 8
  - Use them all!



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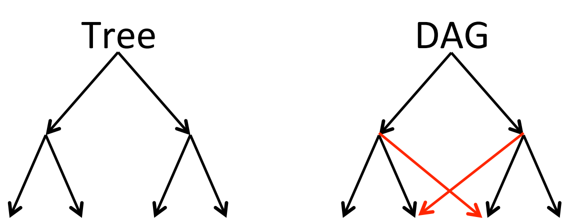
Source "Trees"

- With ECMP, source/sink "tree" is a directed acyclic graph (DAG)
  - Each node has set of next hops
  - Still a compact representation



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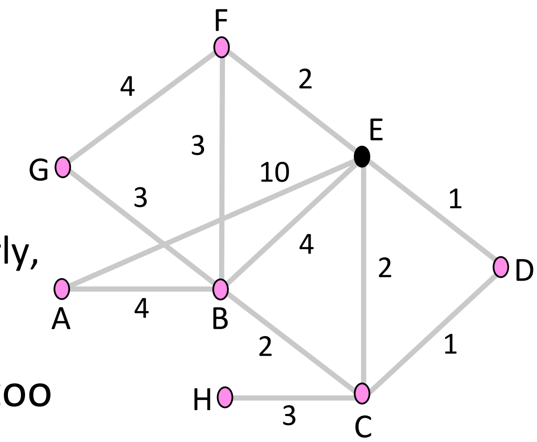
Source "Trees" (2)

- Find the source "tree" for E
  - Procedure is Dijkstra, simply remember set of next hops
  - Compile forwarding table similarly, may have set of next hops
- Straightforward to extend DV too
  - Just remember set of neighbors



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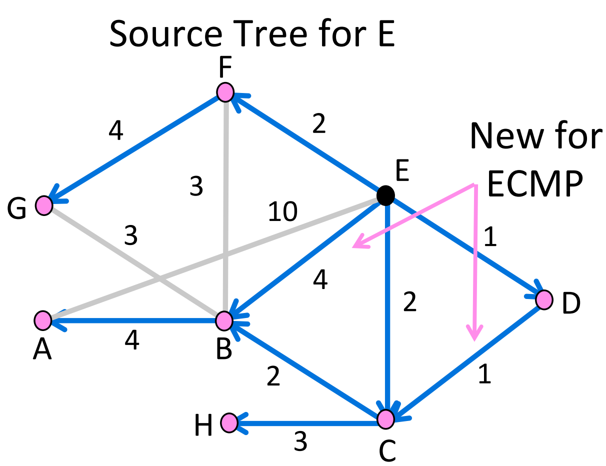
Source "Trees" (3)



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E's Forwarding Table

Node	Next hops
A	B, C, D
B	B, C, D
C	C, D
D	D
E	--
F	F
G	F
H	C, D

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ECMP Forwarding

- Could randomly pick a next hop for each packet based on destination
  - Balances load, but adds jitter
- Instead, try to send packets from a given source/destination pair on the same path
  - Source/destination pair is called a flow
  - Hash flow identifier to next hop
  - No jitter within flow, but less balanced

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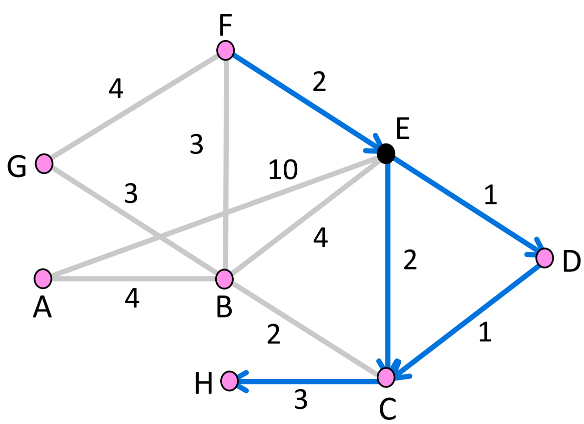
ECMP Forwarding (2)

Multipath routes from F to H



E's Forwarding Choices

Flow	Possible next hops	Example choice
F → H	C, D	D
F → C	C, D	D
E → H	C, D	C
E → C	C, D	C

Use both paths to get to one destination

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IP Prefix Aggregation and Subnets (§5.6.2)

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Introduction to Computer Networks

Routing with Policy (BGP) (§5.6.7)

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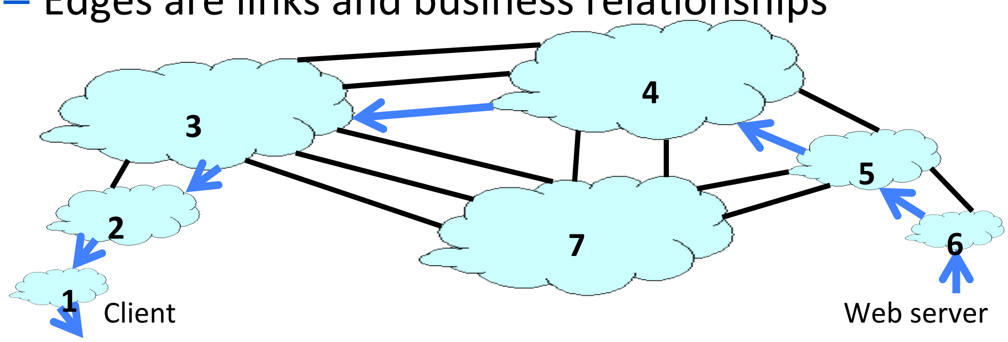
Outline

- Interdomain routing
  - Autonomous Systems (ASes)
- Path-vector routing
  - Flexible path selection
- Business relationships
  - Customer-provider and peer-peer
  - Hierarchy from tier-1 ASes to stubs
- Border Gateway Protocol (BGP)
  - Announcements and withdrawals
  - Import and export policies

Interdomain Routing: Between Networks

- AS-level topology
  - Nodes are Autonomous Systems (ASes)
  - Destinations are prefixes (e.g., 12.0.0.0/8)
  - Edges are links and business relationships



AS Numbers (ASNs)

ASNs are 16 bit values.

Currently around 30,000 in use.

- Level 3: 1
- Harvard: 11
- AT&T: 7018, 6341, 5074, …
- UUNET: 701, 702, 284, 12199, …
- Sprint: 1239, 1240, 6211, 6242, …
- …

ASNs represent units of routing policy

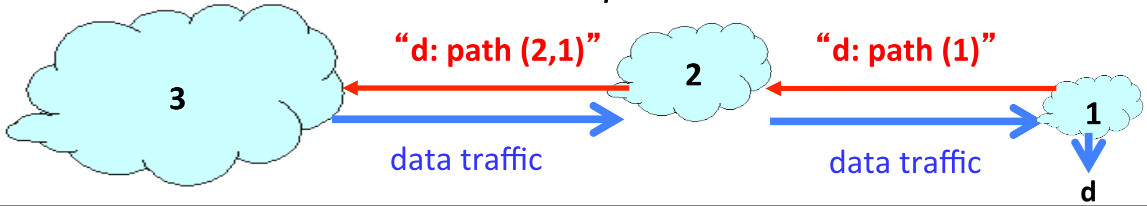
Challenges for Interdomain Routing

- Scale
  - Prefixes: 250,000, and growing
  - ASes: 30,000, and growing
- Privacy
  - ASes don't want to divulge internal topologies
  - … or their business relationships with neighbors
- Policy
  - Need control over where you send traffic
  - … and who can send traffic through you

Policy-Based Path-Vector Routing

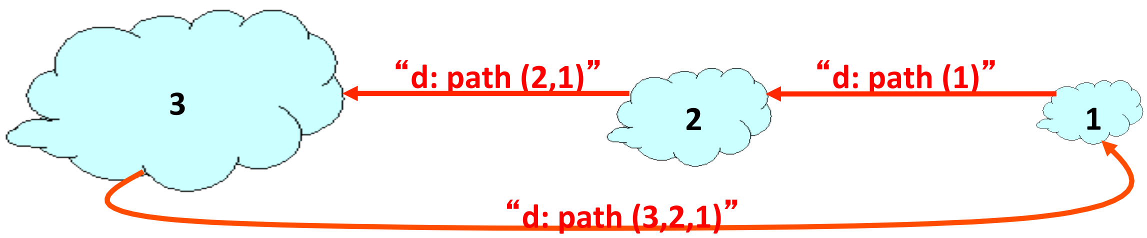
Path-Vector Routing

- Extension of distance-vector routing
  - Support flexible routing policies
  - What are the advantages?
- Key idea: advertise the entire path
  - Distance vector: send *distance metric* per dest d
  - Path vector: send the *entire path* for each dest d



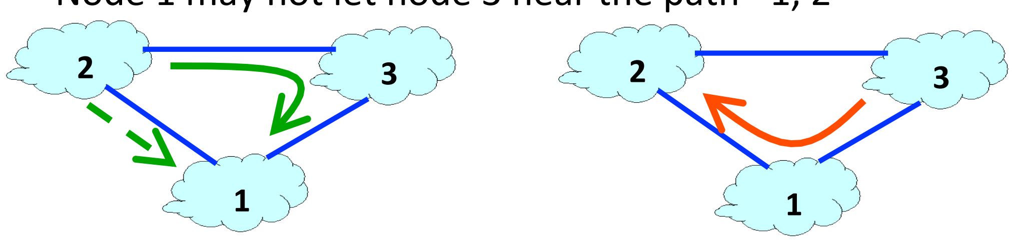
Faster Loop Detection

- Node can easily detect a loop
  - Look for its own node identifier in the path
  - E.g., node 1 sees itself in the path "3, 2, 1"
- Node can simply discard paths with loops
  - E.g., node 1 simply discards the advertisement



Flexible Policies

- Each node can apply local policies
  - Path selection: Which path to use?
  - Path export: Whether to advertise the path?
- Examples
  - Node 2 may prefer the path "2, 3, 1" over "2, 1"
  - Node 1 may not let node 3 hear the path "1, 2"



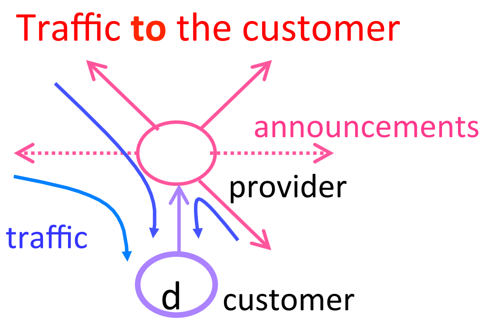
Business Relationships

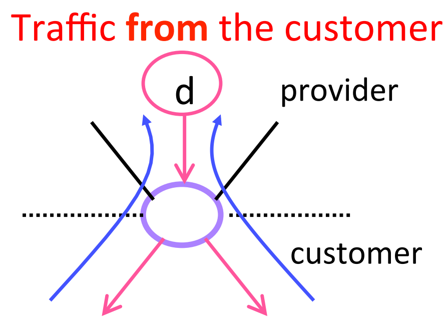
Business Relationships

- Neighboring ASes have business contracts
  - How much traffic to carry
  - Which destinations to reach
  - How much money to pay
- Common business relationships
  - Customer-provider
    - E.g., Princeton is a customer of USLEC
    - E.g., MIT is a customer of Level3
  - Peer-peer
    - E.g., UUNET is a peer of Sprint

Customer-Provider Relationship

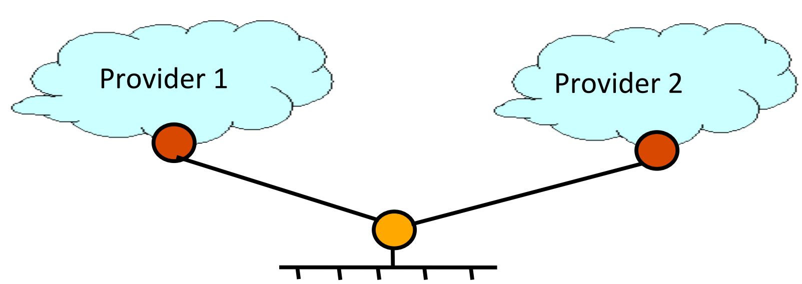
- Customer needs to be reachable from everyone
  - Provider tells all neighbors how to reach the customer
- Customer does not want to provide transit service
  - Customer does not let its providers route through it





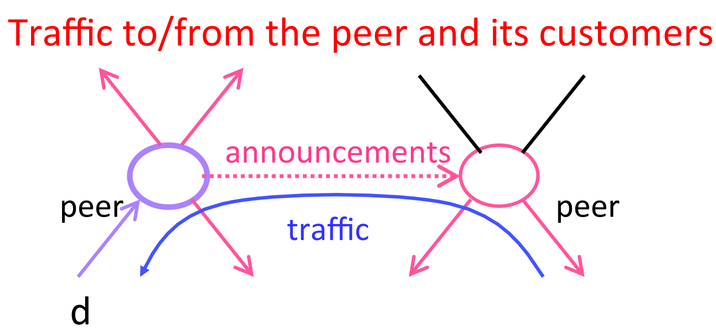
Multi-Homing: Two or More Providers

- Motivations for multi-homing
  - Extra reliability, survive single ISP failure
  - Financial leverage through competition
  - Better performance by selecting better path
  - Gaming the 95th-percentile billing model



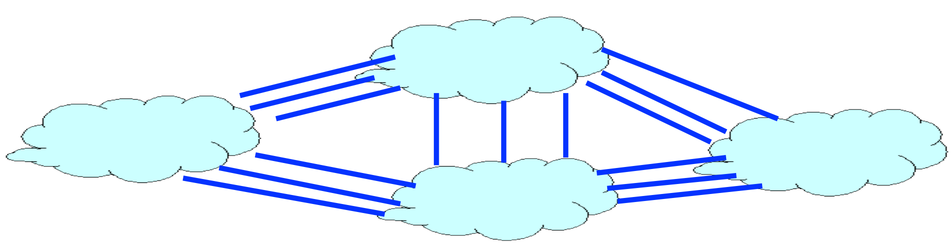
Peer-Peer Relationship

- Peers exchange traffic between customers
  - AS exports *only* customer routes to a peer
  - AS exports a peer's routes *only* to its customers
  - Often the relationship is settlement-free (i.e., no $$$)



AS Structure: Tier-1 Providers

- Tier-1 provider
  - Has no upstream provider of its own
  - Typically has a national or international backbone
- Top of the Internet hierarchy of ~10 ASes
  - AOL, AT&T, Global Crossing, Level3, UUNET, NTT, Qwest, SAVVIS (formerly Cable & Wireless), and Sprint
  - Full peer-peer connections between tier-1 providers



AS Structure: Other ASes

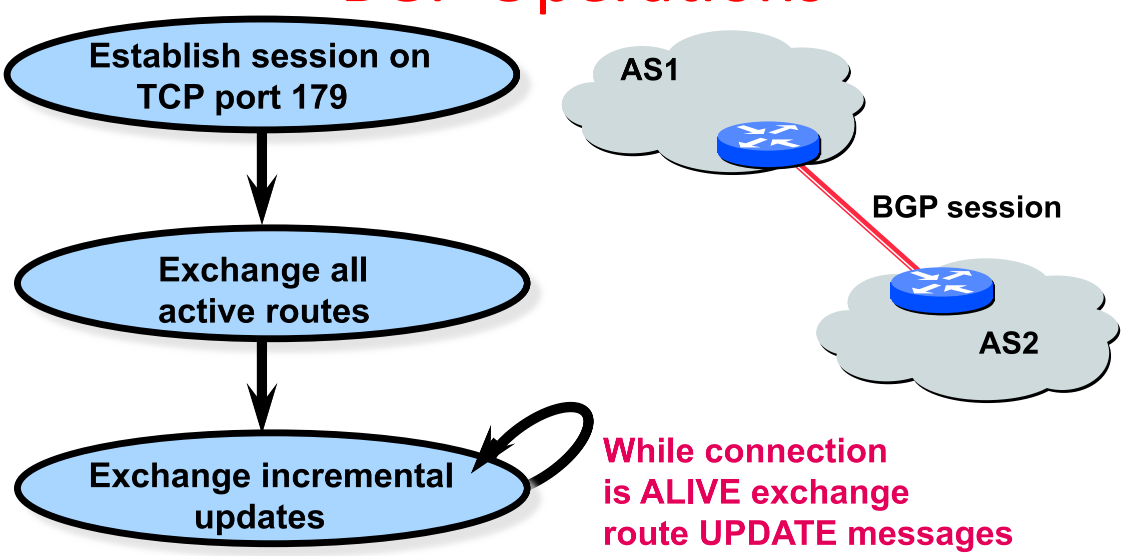
- Other providers
  - Provide transit service to downstream customers
  - … but, need at least one provider of their own
  - Typically have national or regional scope
  - Includes several thousand ASes
- Stub ASes
  - Do not provide transit service to others
  - Connect to one or more upstream providers
  - Includes vast majority (e.g., 85-90%) of the ASes

Border Gateway Protocol

Border Gateway Protocol

- Prefix-based path-vector protocol
- Policy-based routing based on AS Paths
- Evolved during the past 20+ years
  - **1989 : BGP-1 [RFC 1105], replacement for EGP**
  - **1990 : BGP-2 [RFC 1163]**
  - **1991 : BGP-3 [RFC 1267]**
  - **1995 : BGP-4 [RFC 1771], support for CIDR**
  - **2006 : BGP-4 [RFC 4271], update**

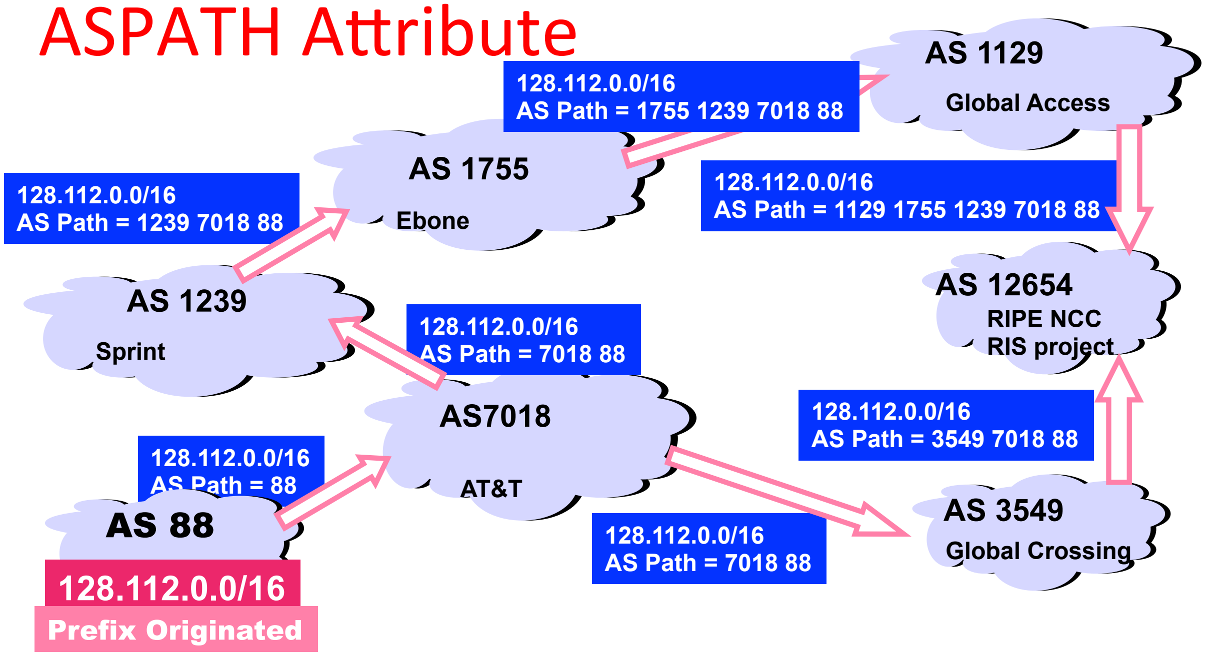
BGP Operations



Incremental Protocol

- A node learns multiple paths to destination
  - Stores all of the routes in a routing table
  - Applies policy to select a single active route
  - … and may advertise the route to its neighbors
- Incremental updates
  - Announcement
    - Upon selecting a new active route, add node id to path
    - … and (optionally) advertise to each neighbor
  - Withdrawal
    - If the active route is no longer available
    - … send a withdrawal message to the neighbors

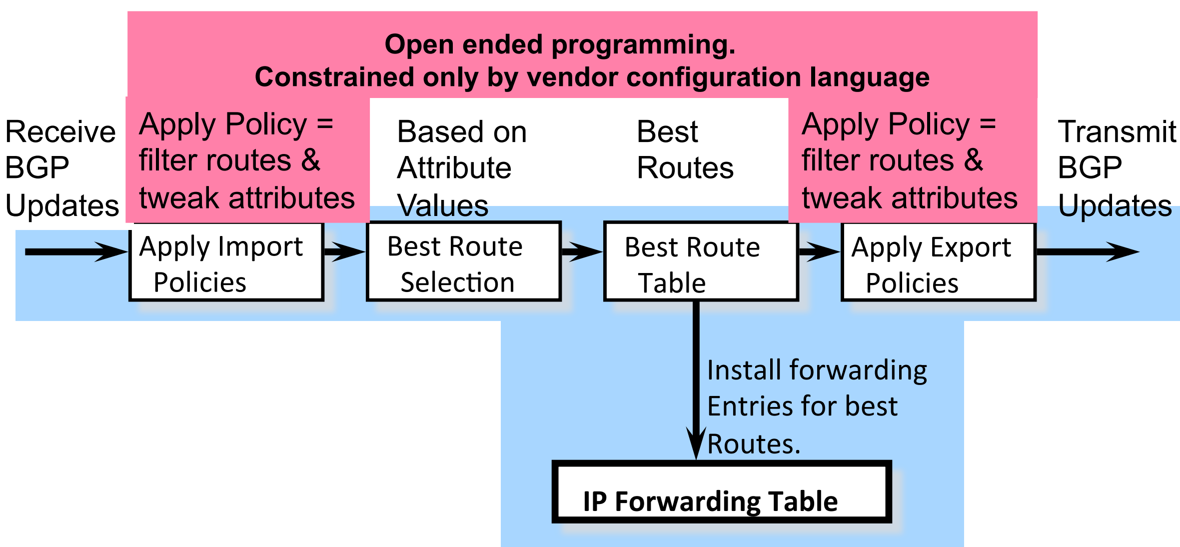
ASPATH Attribute



BGP Policy: Applying Policy to Routes

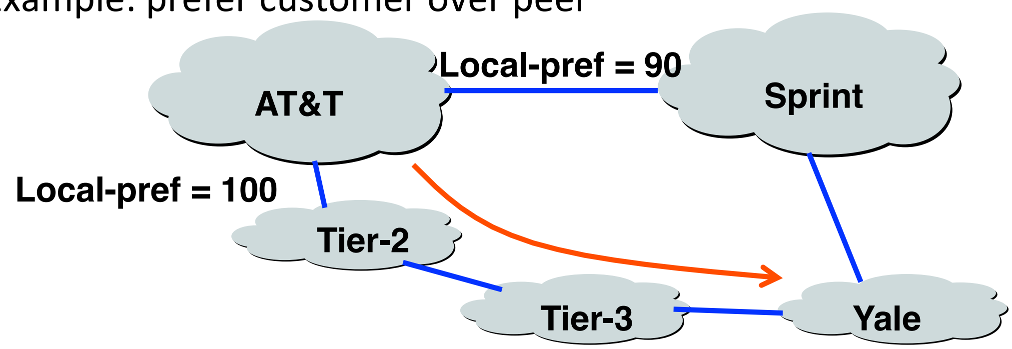
- Import policy
  - Filter unwanted routes from neighbor
    - E.g. prefix that your customer doesn't own
  - Manipulate attributes to influence path selection
    - E.g., assign local preference to favored routes
- Export policy
  - Filter routes you don't want to tell your neighbor
    - E.g., don't tell a peer a route learned from other peer
  - Manipulate attributes to control what they see
    - E.g., make a path look artificially longer than it is

BGP Policy: Influencing Decisions



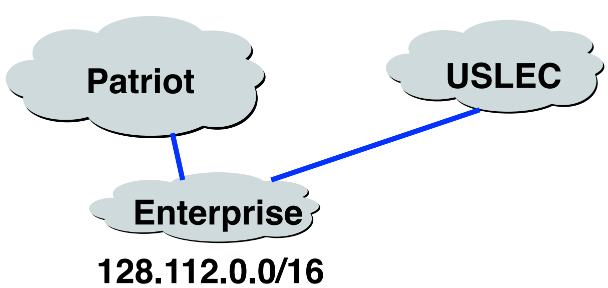
Import Policy: Local Preference

- Favor one path over another
  - Override the influence of AS path length
  - Apply local policies to prefer a path
- Example: prefer customer over peer



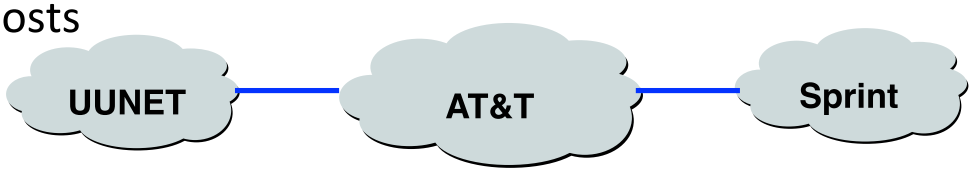
Import Policy: Filtering

- Discard some route announcements
  - Detect configuration mistakes and attacks
- Examples on session to a customer
  - Discard route if prefix not owned by the customer
  - Discard route that contains other large ISP in AS path



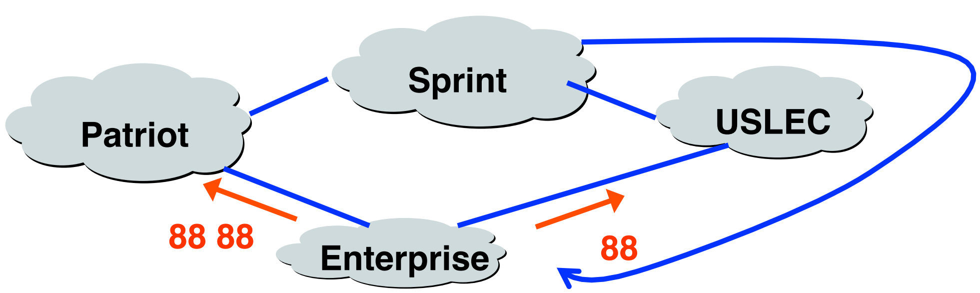
Export Policy: Filtering

- Discard some route announcements
  - Limit propagation of routing information
- Examples
  - Don't announce routes from one peer to another
  - Don't announce routes to network-management hosts



Export Policy: Attribute Manipulation

- Modify attributes of the active route
  - To influence the way other ASes behave
- Example: AS prepending
  - Artificially inflate the AS path length seen by others
  - To convince some ASes to send traffic another way

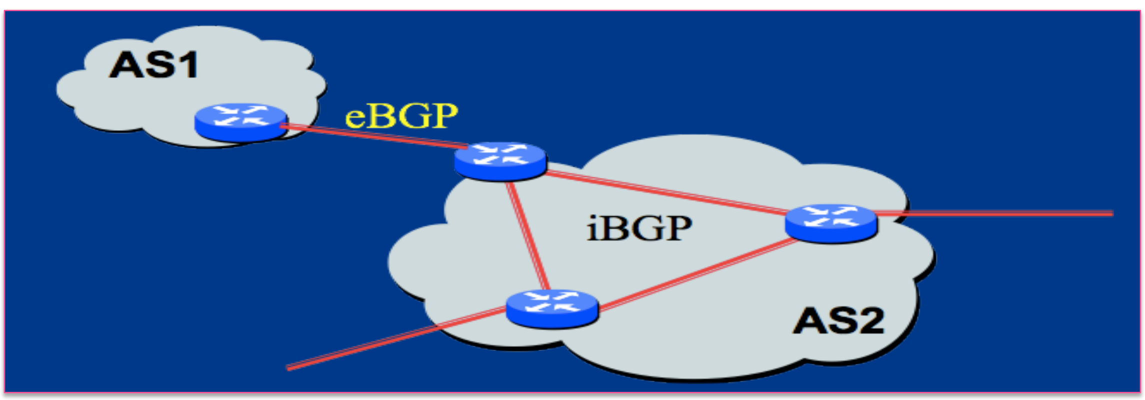


BGP Policy Configuration

- Routing policy languages are vendor-specific
  - Not part of the BGP protocol specification
  - Different languages for Cisco, Juniper, etc.
- Still, all languages have some key features
  - Policy as a list of clauses
  - Each clause matches on route attributes
  - … and either discards or modifies matching routes
- Configuration often done by human operators
  - Implementing the policies of their AS
  - Biz relationships, traffic engineering, security, …

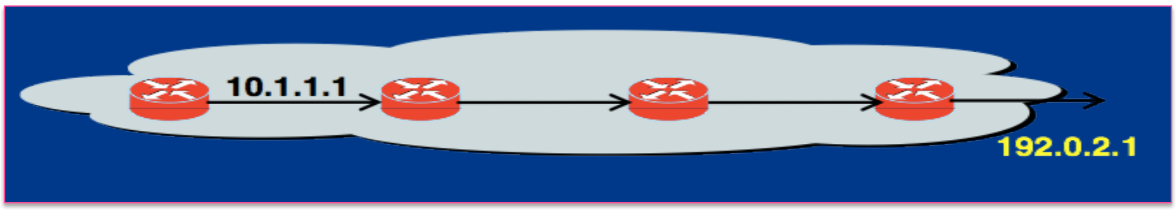
AS is not a single node

- Multiple routers in an AS
  - Need to distribute BGP information within the AS
  - Internal BGP (iBGP) sessions between routers



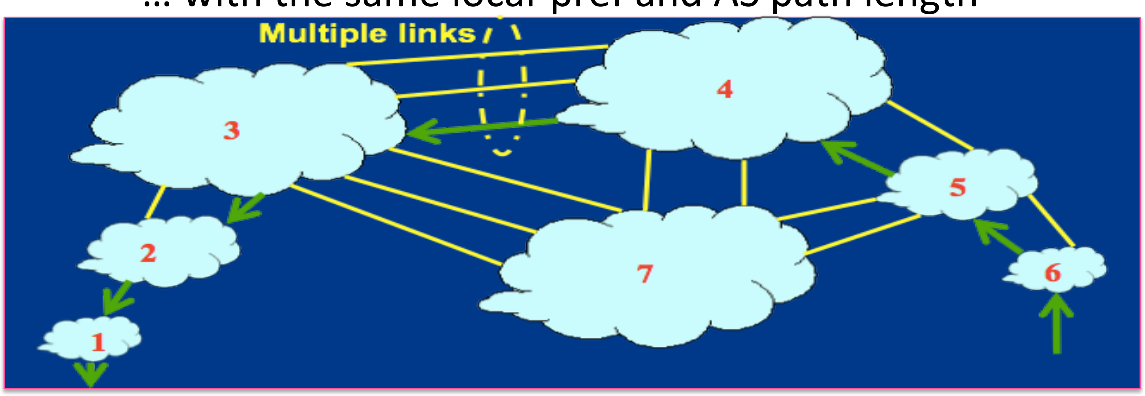
Joining BGP and IGP

- Border Gateway Protocol (BGP)
  - Maps a destination prefix to an egress point
  - 128.112.0.0/16 reached via 192.0.2.1
- Interior Gateway Protocol (IGP)
  - Used to compute paths within the AS
  - Maps an egress point to an outgoing link
  - 192.0.2.1 reached via 10.1.1.1



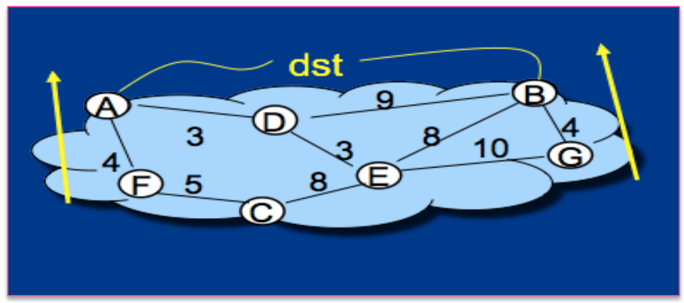
An AS may learn many routes

- Multiple connections to neighboring ASes
  - Multiple border routers may learn good routes
  - … with the same local-pref and AS path length

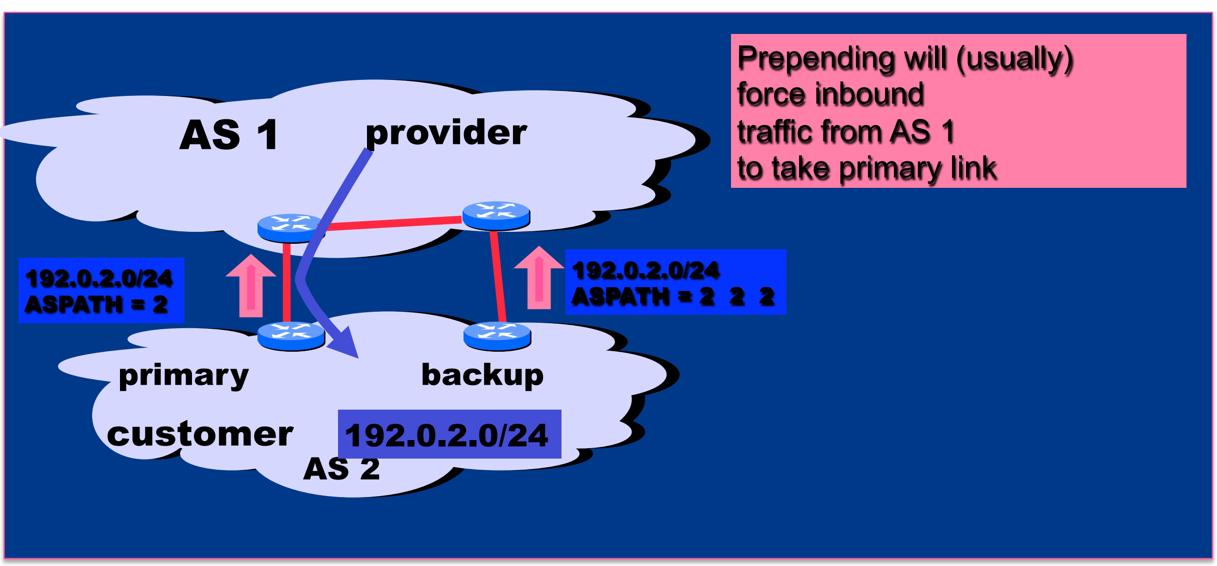


Hot-Potato (Early-Exit) Routing

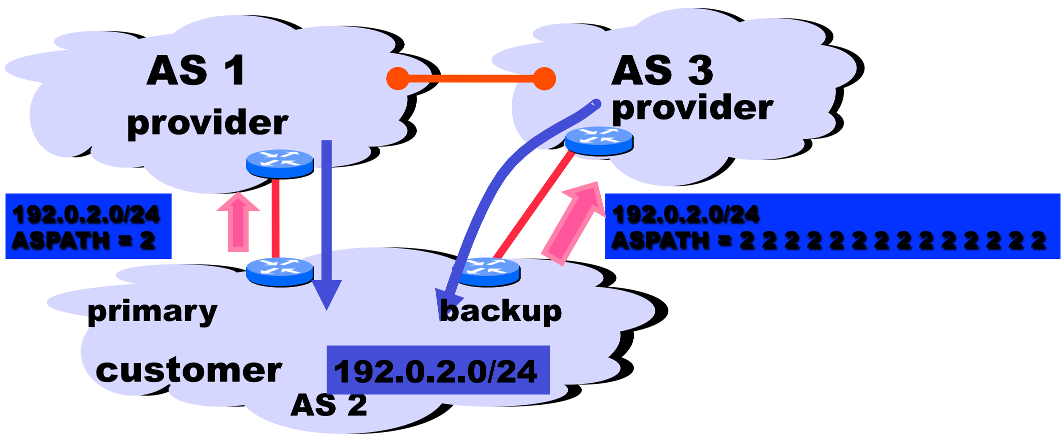
- Hot-potato routing
  - Each router selects the closest egress point
  - … based on the path cost in intradomain protocol
- BGP decision process
  - Highest local preference
  - Shortest AS path
  - Closest egress point
  - Arbitrary tie break



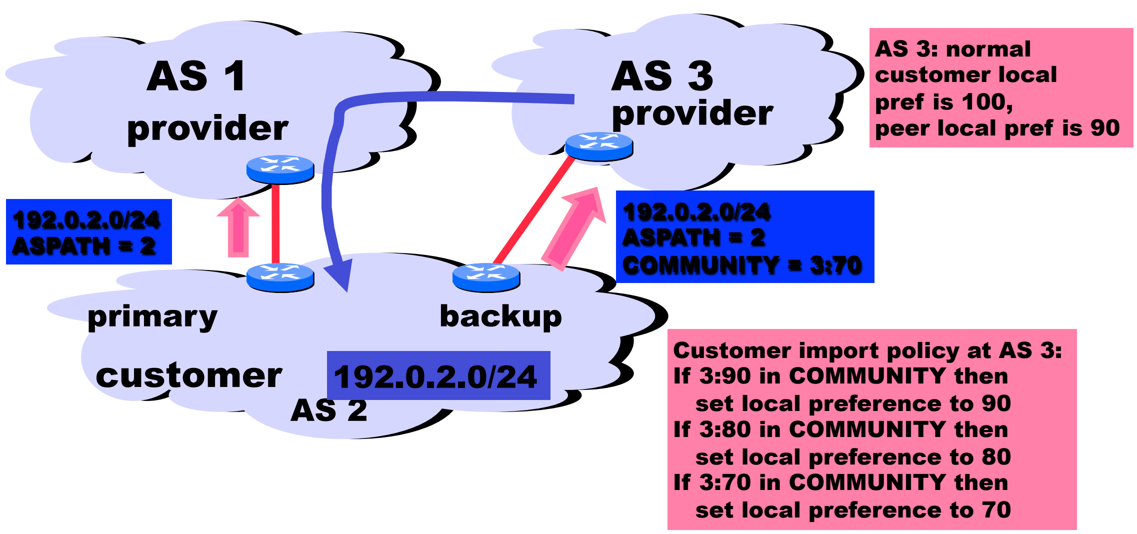
Primary-Backup Paths



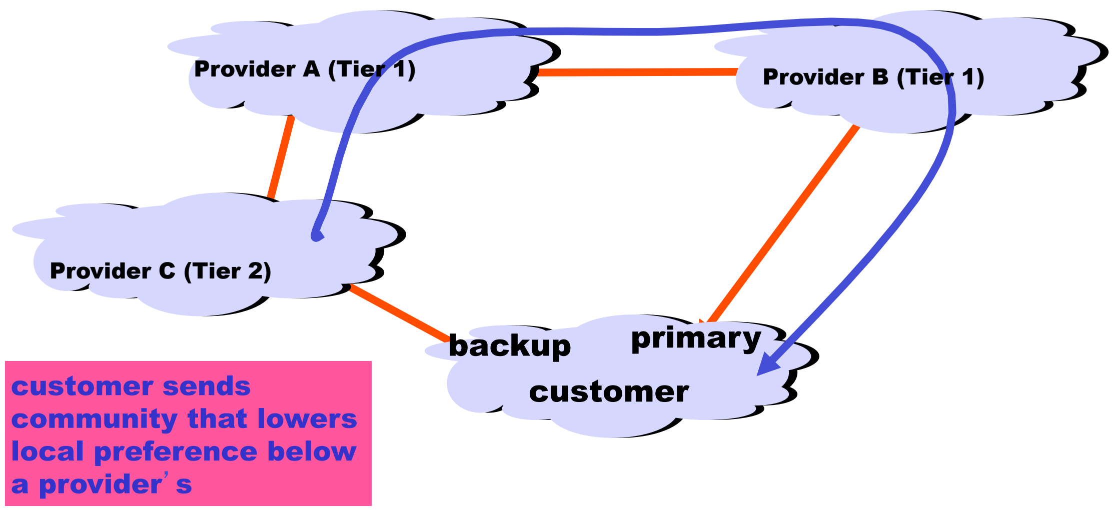
Prepending Doesn't Always Work



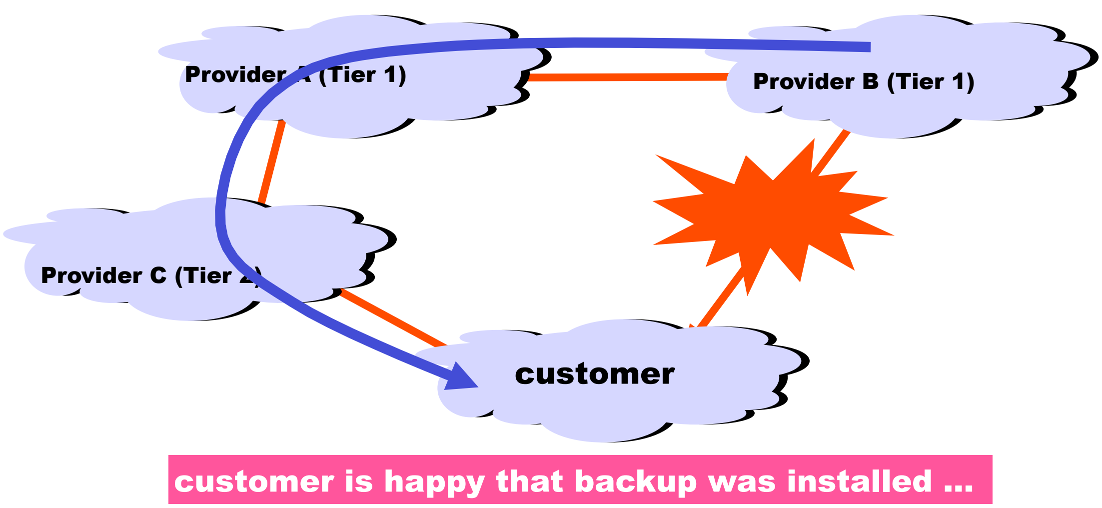
BGP Communities



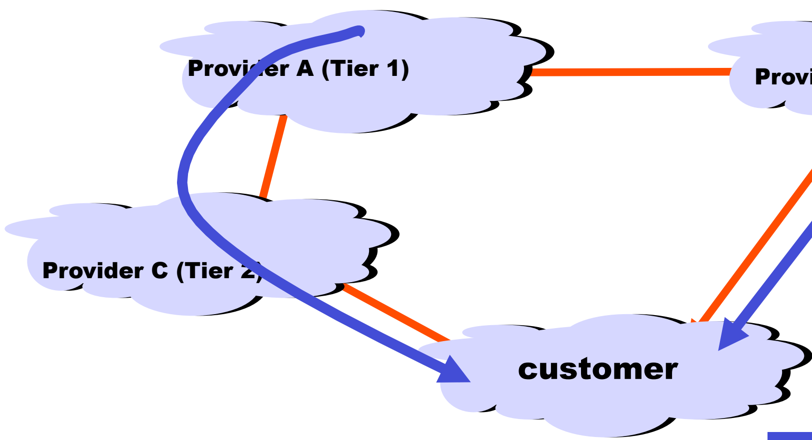
Customer Installs Backup



Failure Happens!



Primary is Repaired...



This is a stable BGP routing!

One "solution" --- reset BGP session on backup link!

BGP Thoughts

- Much more beyond basics to explore!
- Policy is a substantial factor
  - Can we even be independent decisions will be sensible overall?
- Other important factors:
  - Convergence effects
  - How well it scales
  - Integration with intradomain routing
  - And more …

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