CSC 358 – Principles of Computer Networks

Handout # 7: Internet Topology and Routing

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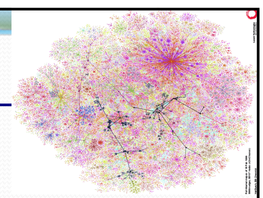
Announcements

- PS2 Due: Fri, Mar 9 @11:59PM
- PA2: Due: Fri, Mar 30 @11:59PM
  - 6% : Working PA1
  - 12%: Working PA2
- Need to work on PA1?
  - Use PA1-Test on MarkUs
- PA2 Autotester running on MarkUs
- Finals: Mon, Apr 9, 2018 from 9-12 in IB120
  - Please consult the official timetable website https://student.utm.utoronto.ca/examschedule/finalexams.php

Outline

- Internet's Topology
  - Internet's two-tiered topology
  - AS-level topology
  - Router-level topology
- Routing in the Internet
  - Hierarchy and Autonomous Systems
  - Interior Routing Protocols: RIP, OSPF
  - Exterior Routing Protocol: BGP

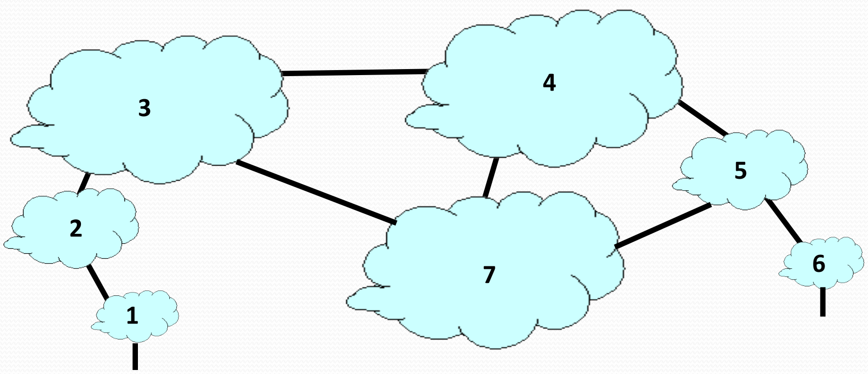
Internet Routing Architecture



- Divided into Autonomous Systems
  - Distinct regions of administrative control
  - Routers/links managed by a single "institution"
  - Service provider, company, university, …
- Hierarchy of Autonomous Systems
  - Large, tier-1 provider with a nationwide backbone
  - Medium-sized regional provider with smaller backbone
  - Small network run by a single company or university
- Interaction between Autonomous Systems
  - Internal topology is not shared between AS's
  - … but, neighboring AS's interact to coordinate routing

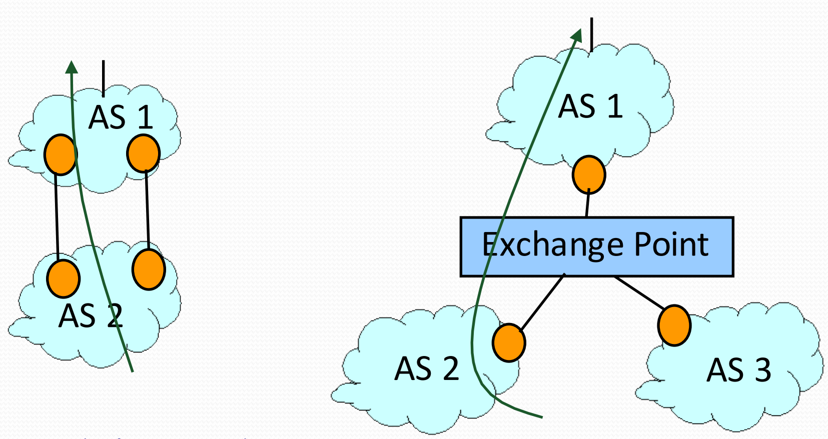
AS Topology

- Node: Autonomous System
- Edge: Two AS's that connect to each other



What is an Edge, Really?

- Edge in the AS graph
  - At least one connection between two AS's
  - Some destinations reached from one AS via the other



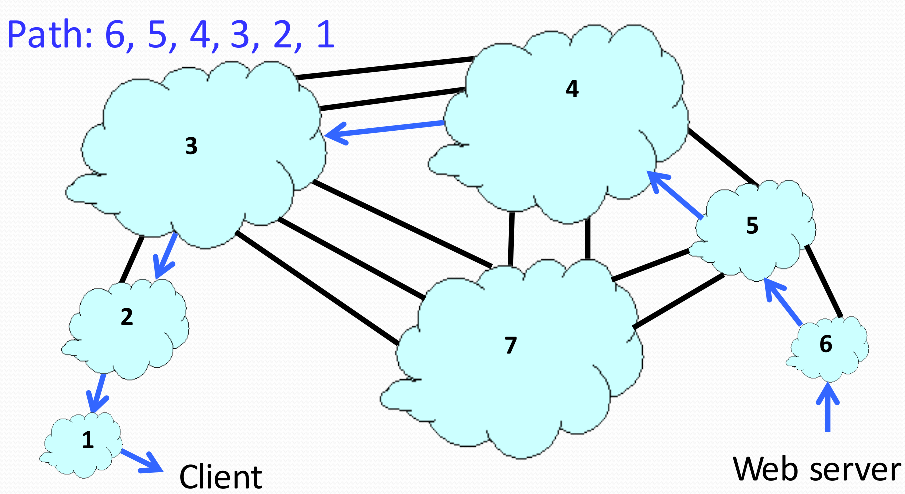
Identifying Autonomous Systems

AS Numbers are 32 bit values (used to be 16)

Currently just over 54,000 in use.

- Level 3: 1
- MIT: 3
- Harvard: 11
- Yale: 29
- U of T: 239
- AT&T: 7018, 6341, 5074, …
- UUNET: 701, 702, 284, 12199, …
- Sprint: 1239, 1240, 6211, 6242, …
- …

Interdomain Paths



Business Relationships

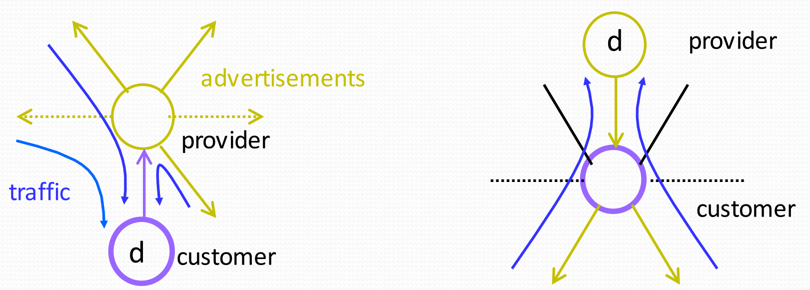
- Neighboring AS's have business contracts
  - How much traffic to carry
  - Which destinations to reach
  - How much money to pay
- Common business relationships
  - Customer-provider
    - E.g., Princeton is a customer of AT&T
    - E.g., MIT is a customer of Level 3
  - Peer-peer
    - E.g., Princeton is a peer of Patriot Media
    - E.g., AT&T 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

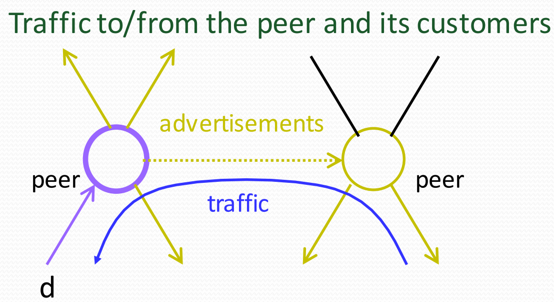
Traffic **to** the customer

Traffic **from** the customer



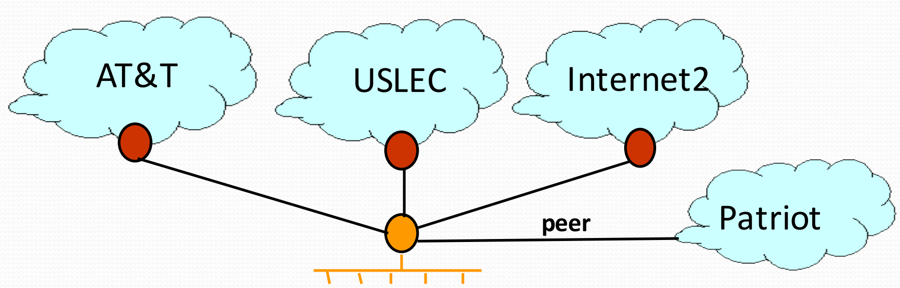
Peer-Peer Relationship

- 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 $$$)



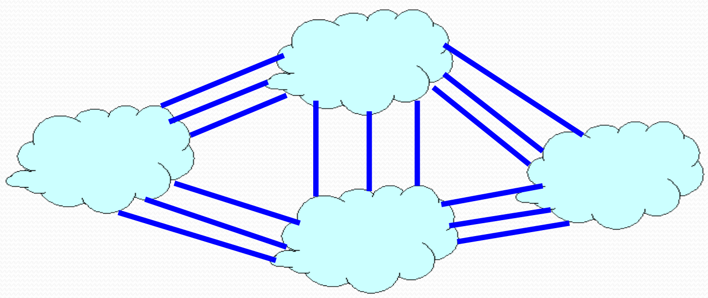
Princeton Example

- Internet: customer of AT&T and USLEC
- Research universities/labs: customer of Internet2
- Local residences: peer with Patriot Media
- Local non-profits: provider for several non-profits



AS Structure: Tier-1 Providers

- Tier-1 provider
  - Has no upstream provider of its own
  - Typically has a national or international backbone
  - UUNET, Sprint, AT&T, Level 3, …
- Top of the Internet hierarchy of 12-20 AS's
  - Full peer-peer connections between tier-1 providers

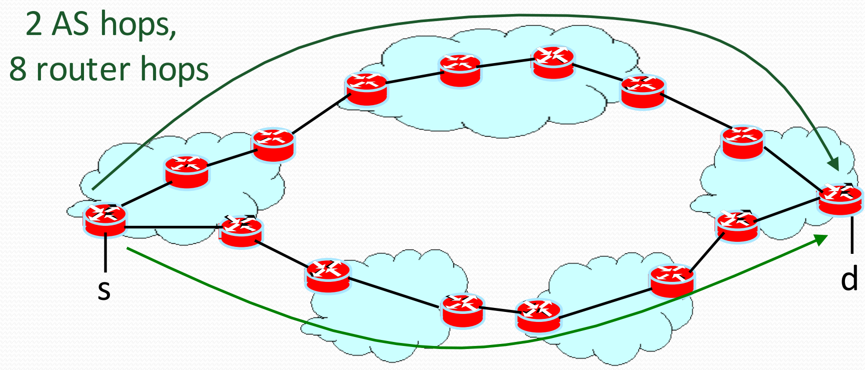


AS Structure: Other AS's

- Tier-2 providers
  - Provide transit service to downstream customers
  - … but, need at least one provider of their own
  - Typically have national or regional scope
  - E.g., Minnesota Regional Network
  - Includes a few thousand of the AS's
- Stub AS's
  - Do not provide transit service to others
  - Connect to one or more upstream providers
  - Includes vast majority (e.g., 85-90%) of the AS's

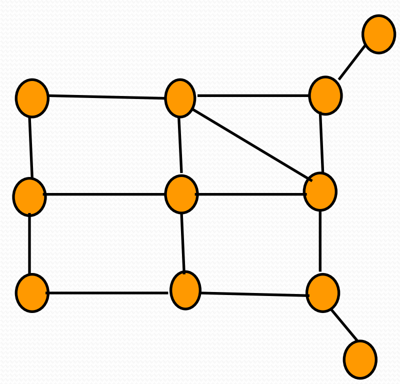
Characteristics of AS Paths

- AS path may be longer than shortest AS path
- Router path may be longer than shortest path

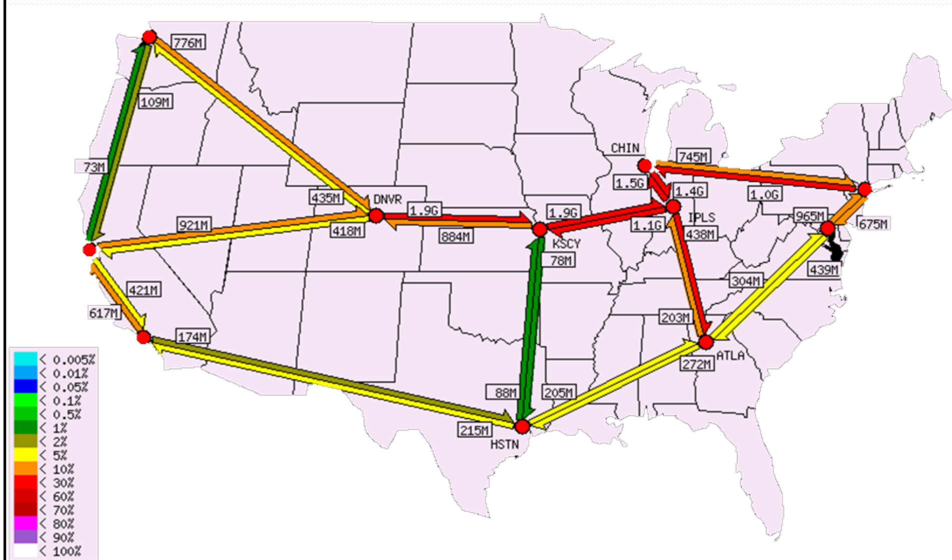


Backbone Networks

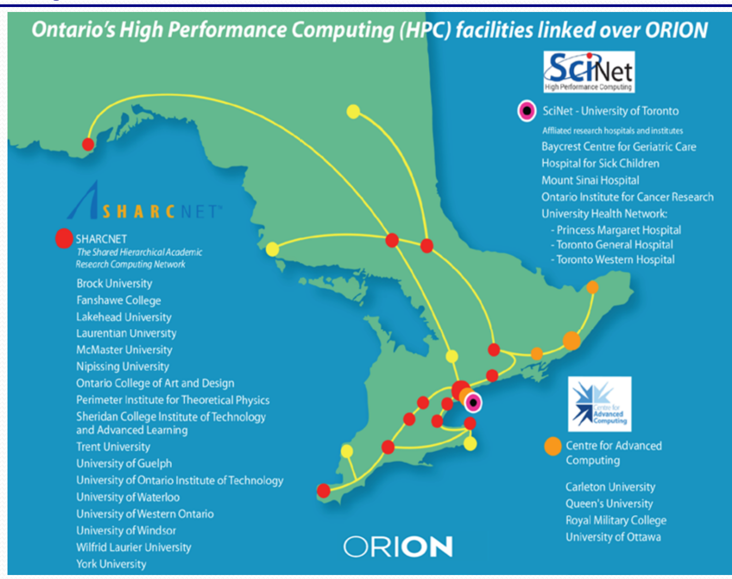
- Backbone networks
  - Multiple Points-of-Presence (PoPs)
  - Lots of communication between PoPs
  - Accommodate traffic demands and limit delay



Example: Abilene Internet2 Backbone

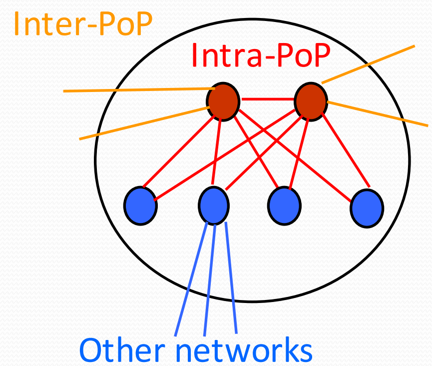


Example: Orion Network



Points-of-Presence (PoPs)

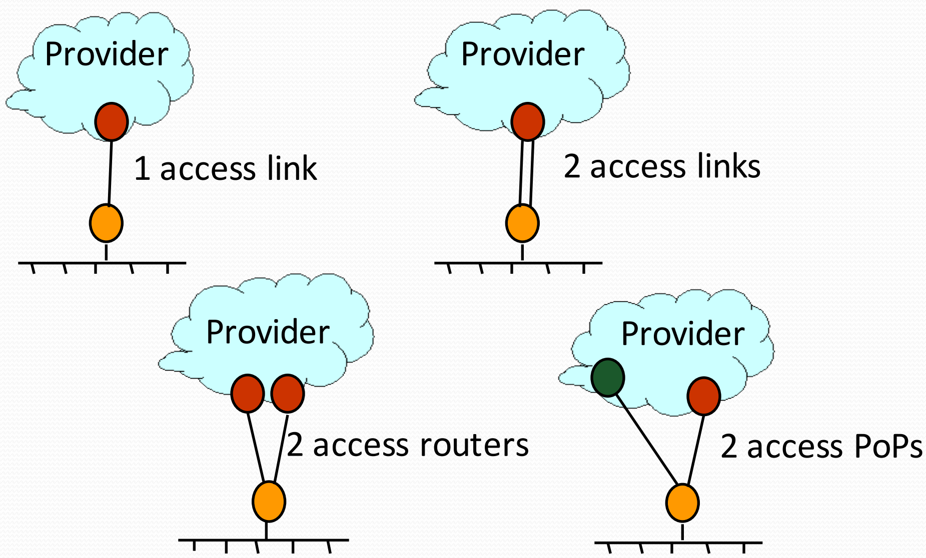
- Inter-PoP links
  - Long distances
  - High bandwidth
- Intra-PoP links
  - Short cables between racks or floors
  - Aggregated bandwidth
- Links to other networks
  - Wide range of media and bandwidth



Where to Locate Nodes and Links

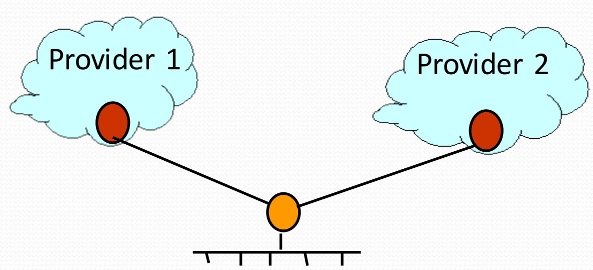
- Placing Points-of-Presence (PoPs)
  - Large population of potential customers
  - Other providers or exchange points
  - Cost and availability of real-estate
  - Mostly in major metropolitan areas
- Placing links between PoPs
  - Already fiber in the ground
  - Needed to limit propagation delay
  - Needed to handle the traffic load

Customer Connecting to a Provider



Multi-Homing: Two or More Providers

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



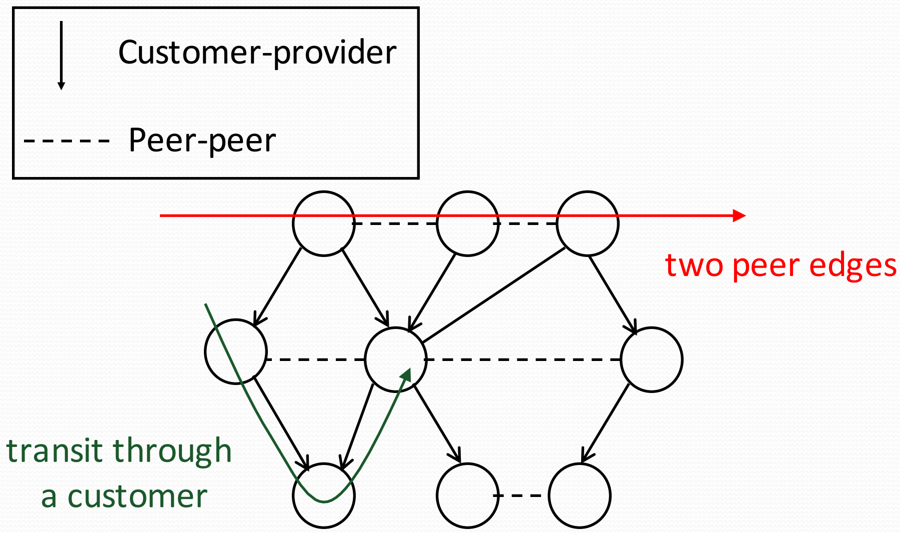
Inferring the AS-Level Topology

- Collect AS paths from many vantage points
  - Learn a large number of AS paths
  - Extract the nodes and the edges from the path
- Example: AS path "1 7018 88" implies
  - Nodes: 1, 7018, and 88
  - Edges: (1, 7018) and (7018, 88)
- Ways to collect AS paths from many places
  - Mapping traceroute data to the AS level
    - Map using whois
    - Example: try whois –h whois.arin.net "MCI Worldcom"
  - Measurements of the interdomain routing protocol

Inferring AS Relationships

- Key idea
  - The business relationships determine the routing policies
  - The routing policies determine the paths that are chosen
  - So, look at the chosen paths and infer the policies
- Example: AS path "1 7018 88" implies
  - AS 7018 allows AS 1 to reach AS 88
  - AT&T allows Level 3 to reach Princeton
  - Each "triple" tells something about transit service
- Collect and analyze AS path data
  - Identify which AS's can transit through the other
  - … and which other AS's they are able to reach this way

Paths You Should Never See ("Invalid")



Challenges of Relationship Inference

- Incomplete measurement data
  - Hard to get a complete view of the AS graph
  - Especially hard to see peer-peer edges low in hierarchy
- Real relationships are sometime more complex
  - Peer in one part of the world, customer in another
  - Other kinds of relationships (e.g., backup)
  - Special relationships for certain destination prefixes
- Still, inference work has proven very useful
  - Qualitative view of Internet topology and relationships

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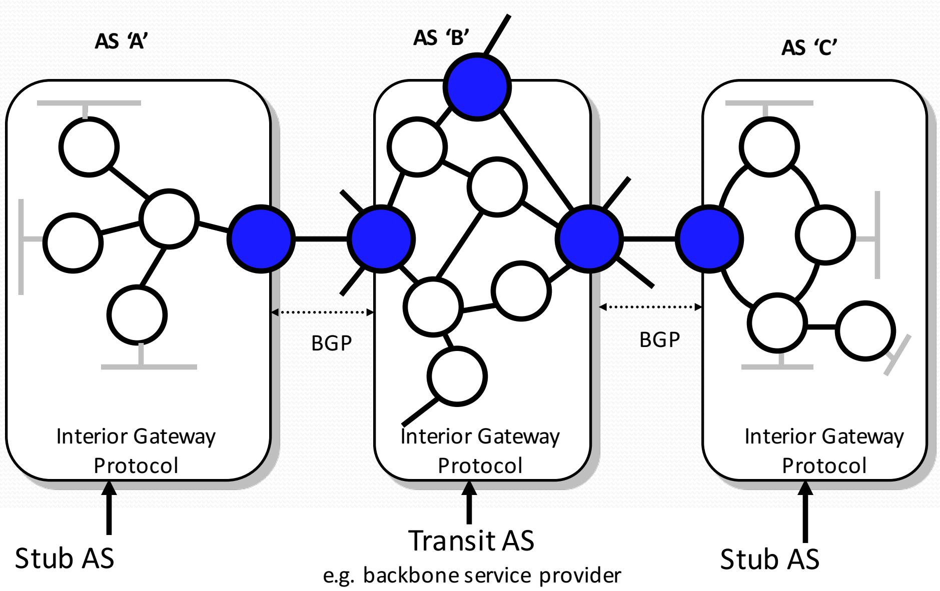
Routing Story So Far …

- Techniques
  - Flooding
  - Distributed Bellman Ford Algorithm
  - Dijkstra's Shortest Path First Algorithm
- Question 1. Can we apply these to the Internet as a whole?
- Question 2. If not, what can we do?

Routing in the Internet

- The Internet uses hierarchical routing.
- Within an AS, the administrator chooses an Interior Gateway Protocol (IGP)
  - Examples of IGPs: RIP (rfc 1058), OSPF (rfc 1247, IS-IS (rfc 1142).
- Between AS's, the Internet uses an Exterior Gateway Protocol
  - AS's today use the Border Gateway Protocol, BGP-4 (rfc 1771)

Routing in the Internet

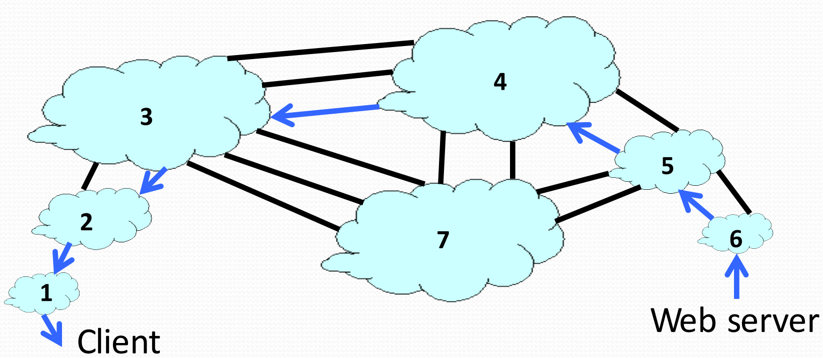


Interior Routing Protocols

- RIP (Routing Information Protocol)
  - Uses distance vector (distributed Bellman-Ford algorithm).
  - Updates sent every 30 seconds.
  - No authentication.
  - Originally in BSD UNIX.
  - Widely used for many years; not used much anymore.
- OSPF (Open Shortest Path First)
  - Link-state updates sent (using flooding) as and when required.
  - Every router runs Dijkstra's algorithm.
  - Authenticated updates.
  - Autonomous system may be partitioned into "areas".
  - Widely used.

Interdomain Routing

- AS-level topology
  - Destinations are IP prefixes (e.g., 12.0.0.0/8)
  - Nodes are Autonomous Systems (AS's)
  - Links are connections & business relationships



Challenges for Interdomain Routing

- Scale
  - Prefixes: 150,000-500,000, and growing
  - AS's: 54,000 visible ones, and growing
  - AS paths and routers: at least in the millions…
- Privacy
  - AS's don't want to divulge internal topologies
  - … or their business relationships with neighbors
- Policy
  - No Internet-wide notion of a link cost metric
  - Need control over where you send traffic
  - … and who can send traffic through you

Link-State Routing is Problematic

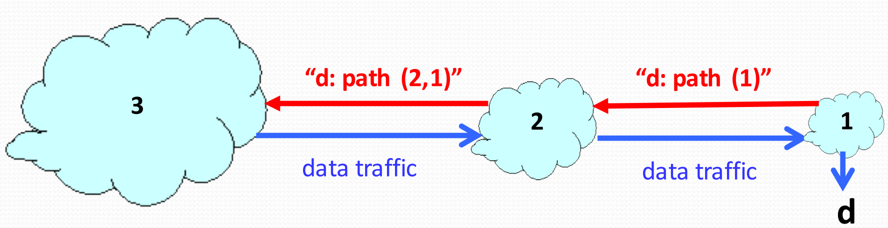
- Topology information is flooded
  - High bandwidth and storage overhead
  - Forces nodes to divulge sensitive information
- Entire path computed locally per node
  - High processing overhead in a large network
- Minimizes some notion of total distance
  - Works only if policy is shared and uniform
- Typically used only inside an AS
  - E.g., OSPF and IS-IS

Distance Vector is on the Right Track

- Advantages
  - Hides details of the network topology
  - Nodes determine only "next hop" toward the dest
- Disadvantages
  - Minimizes some notion of total distance, which is difficult in an interdomain setting
  - Slow convergence due to the counting-to-infinity problem ("bad news travels slowly")
- Idea: extend the notion of a distance vector

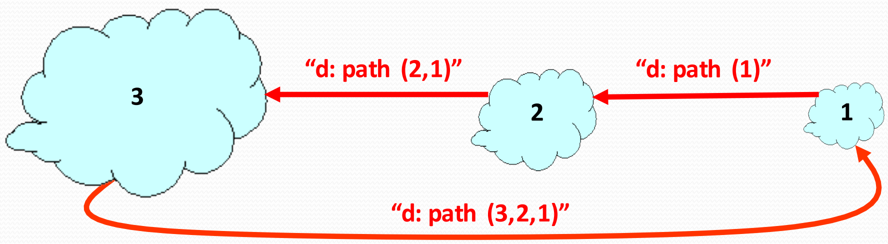
Path-Vector Routing

- Extension of distance-vector routing
  - Support flexible routing policies
  - Avoid count-to-infinity problem
- 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



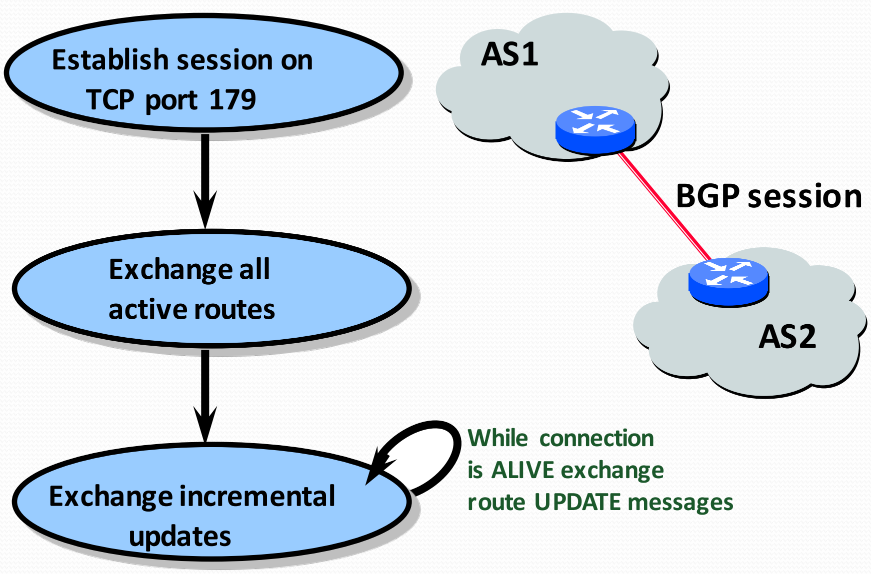
Border Gateway Protocol (BGP-4)

- BGP is a path-vector routing protocol.
- BGP advertises complete paths (a list of AS's).
  - Also called AS_PATH (this is the path vector)
  - Example of path advertisement: "The network 171.64/16 can be reached via the path {AS1, AS5, AS13}".
- Paths with loops are detected locally and ignored.
- Local policies pick the preferred path among options.
- When a link/router fails, the path is "withdrawn".

BGP

- BGP provides each AS a means to:
  - eBGP: obtain subnet reachability information from neighboring ASes
  - iBGP: propagate reachability information to all AS-internal routers.
  - determine "good" routes to other networks based on reachability information and *policy*
- allows subnet to advertise its existence to rest of Internet: *"I am here"*

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

BGP Messages

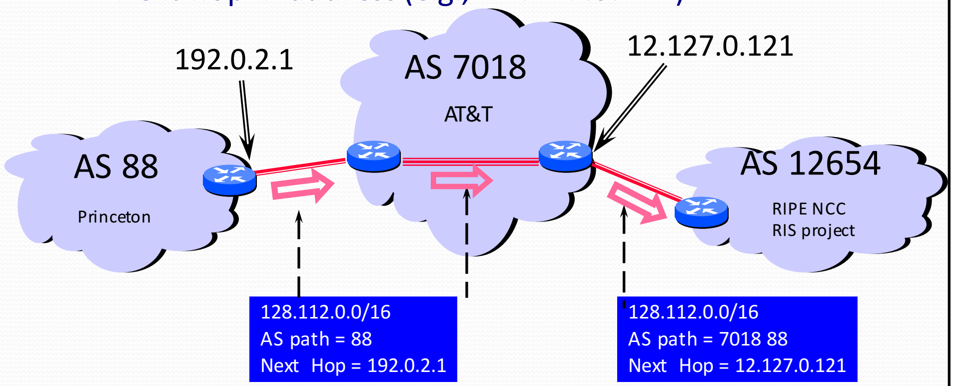
- Open : Establish a BGP session.
- Keep Alive : Handshake at regular intervals.
- Notification : Shuts down a peering session.
- Update : Announcing new routes or withdrawing previously announced routes.

BGP announcement = prefix + path attributes

- Attributes include: Next hop, AS Path, local preference, Multi-exit discriminator, …
  - Used to select among multiple options for paths

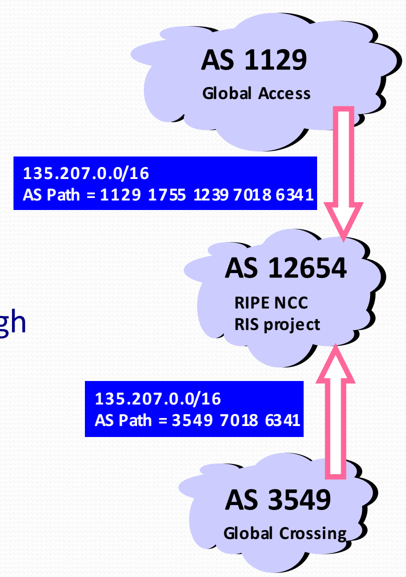
BGP Route

- Destination prefix (e.g,. 128.112.0.0/16)
- Route attributes, including
  - AS path (e.g., “7018 88”)
  - Next-hop IP address (e.g., 12.127.0.121)



BGP Path Selection

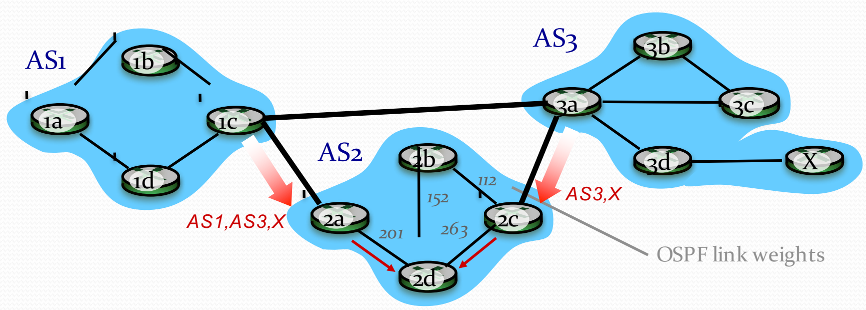
- Simplest case
  - Shortest AS path
  - Arbitrary tie break
- Example
  - Three-hop AS path preferred over a four-hop AS path
  - AS 12654 prefers path through Global Crossing
- But, BGP is not limited to shortest-path routing
  - Policy-based routing



BGP Route Selection

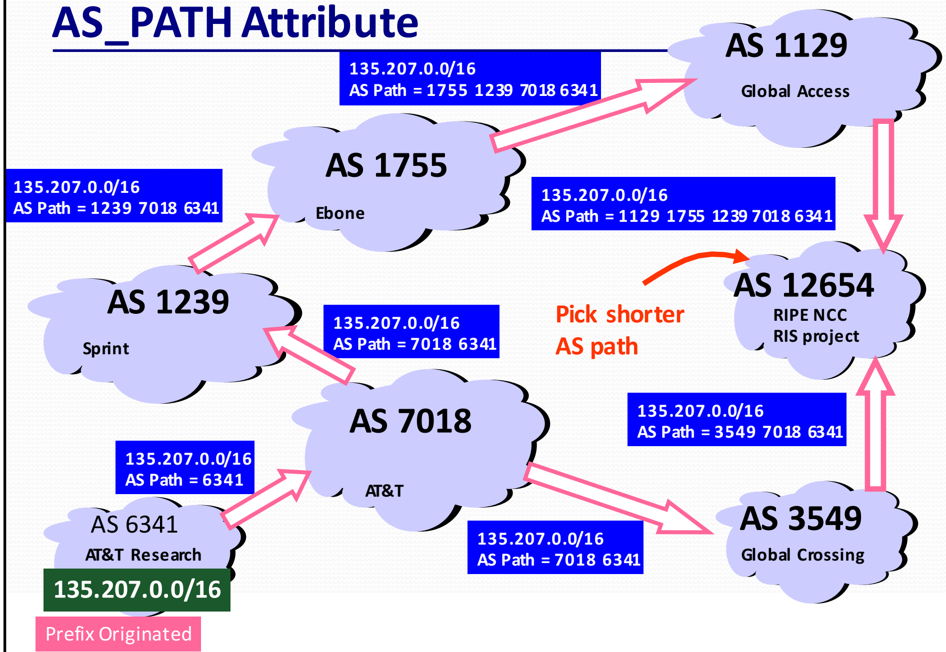
1. local preference value attribute: policy decision
2. shortest AS-PATH
3. closest NEXT-HOP router: hot potato routing
4. additional criteria

Hot Potato Routing



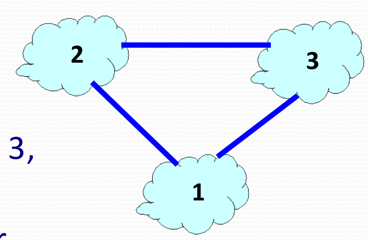
- 2d learns (via iBGP) it can route to X via 2a or 2c
- *hot potato routing:* choose local gateway that has least intra-domain cost (e.g., 2d chooses 2a, even though more AS hops to *X*): don't worry about inter-domain cost!

AS_PATH Attribute

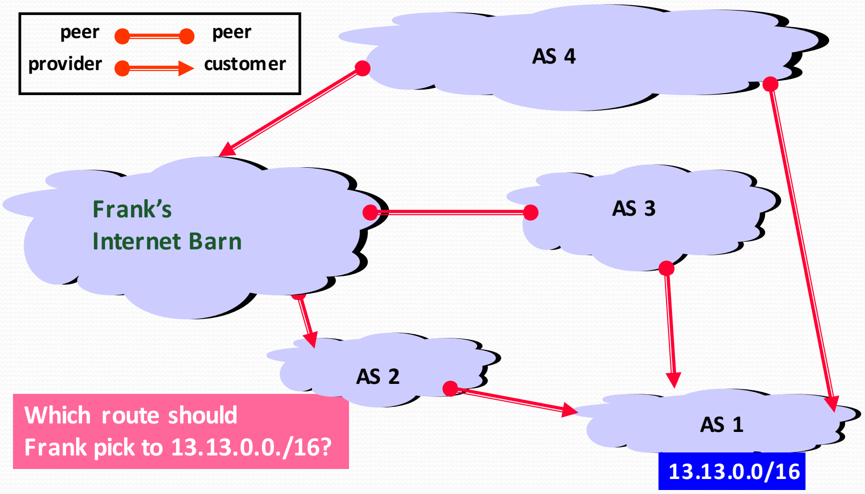


Flexible Policies

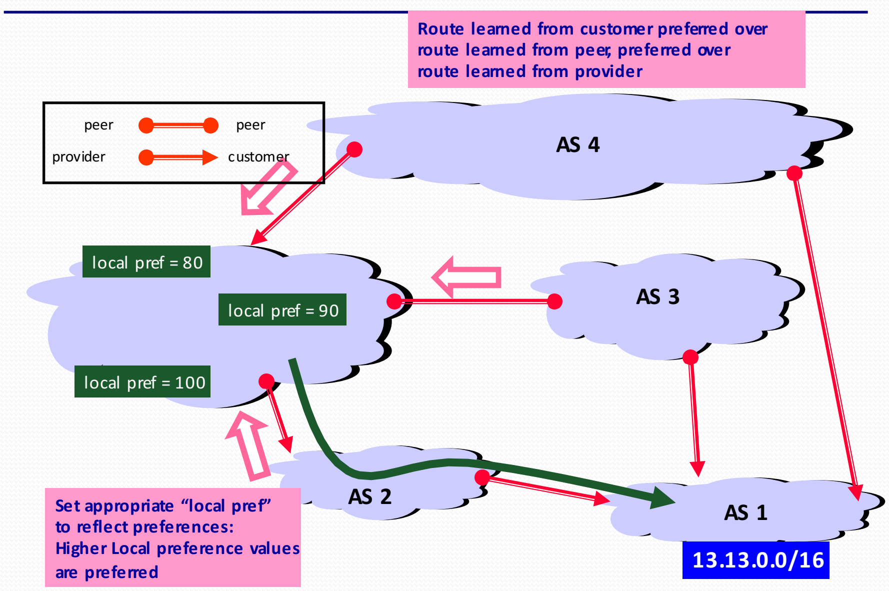
- Each node can apply local policies
  - Path selection: Which path to use?
  - Path export: Which paths to advertise?
- Examples
  - Node 2 may prefer the path "2, 3, 1" over "2, 1"
  - Node 1 may not let node 3 hear the path "1, 2"



So Many Choices…



Frank's Choices…



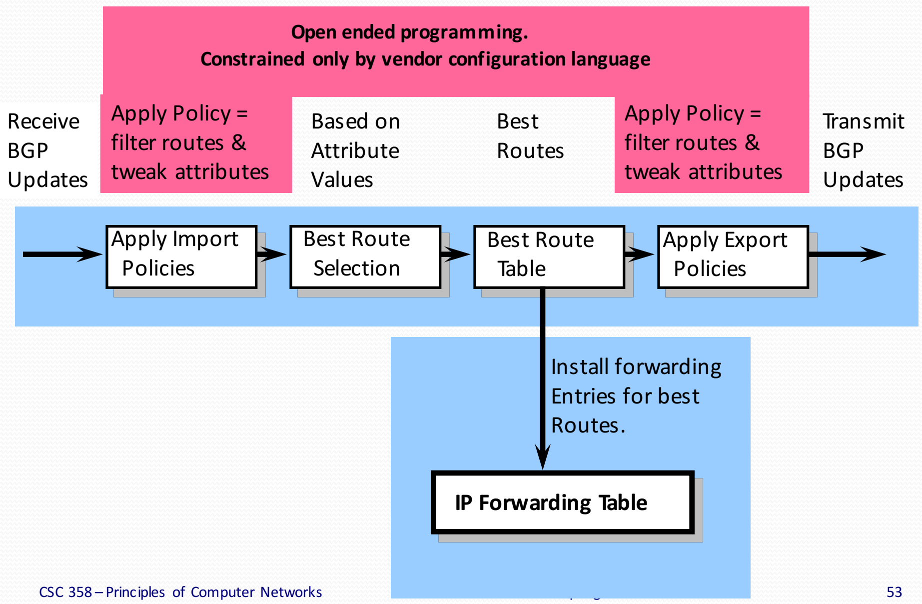
BGP Route Selection Summary

Highest Local Preference	Enforce relationships E.g. prefer customer routes over peer routes
Shortest ASPATH Lowest MED i-BGP < e-BGP Lowest IGP cost to BGP egress	traffic engineering
Lowest router ID	Throw up hands and break ties

BGP Policy: Applying Policy to Routes

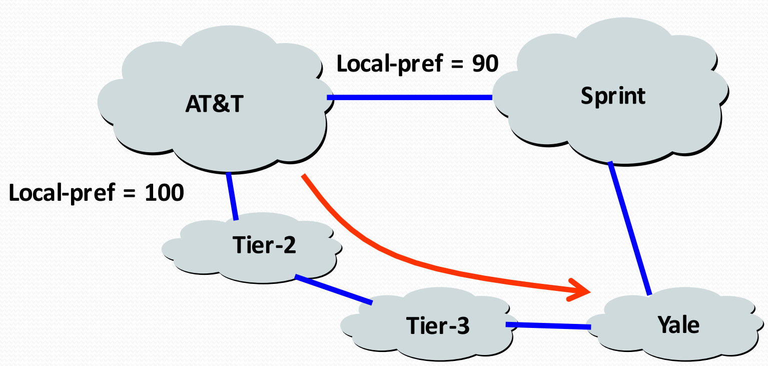
- Import policy
  - Filter unwanted routes from neighbor
    - E.g. prefix that your customer doesn't own
  - Manipulate attributes to influence path selection
    - E.g., assign local preference to favored routes
- Export policy
  - Filter routes you don't want to tell your neighbor
    - E.g., don't 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



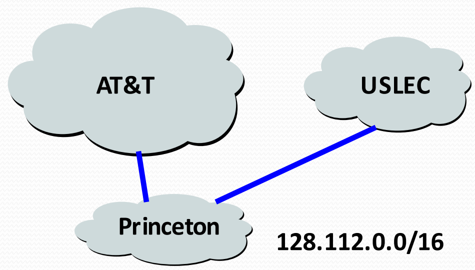
Import Policy: Local Preference

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



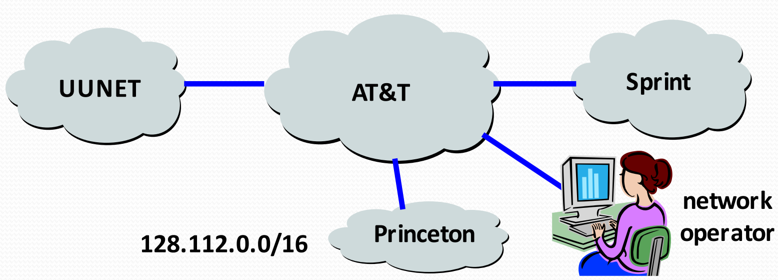
Import Policy: Filtering

- 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



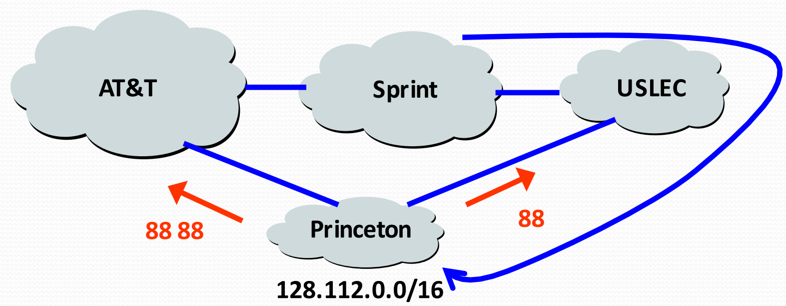
Export Policy: Filtering

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



Export Policy: Attribute Manipulation

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

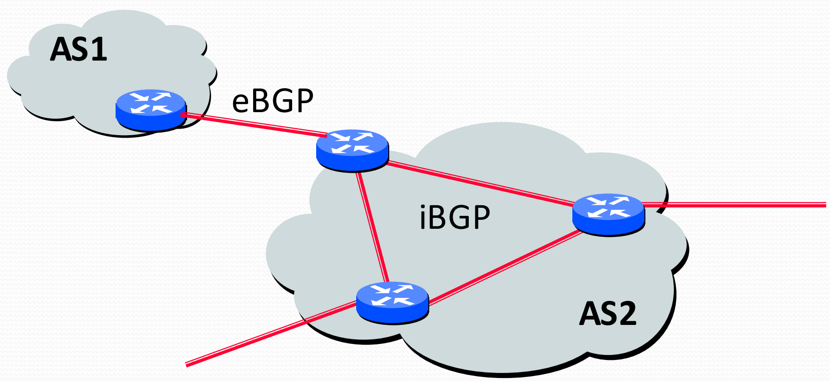


BGP Policy Configuration

- 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 the matching routes
- Configuration done by human operators
  - Implementing the policies of their AS
  - Business relationships, traffic engineering, security, …
  - http://www.cs.princeton.edu/~jrex/papers/policies.pdf

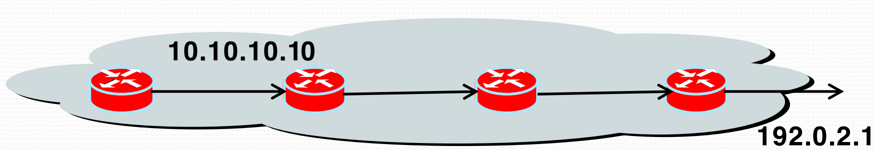
AS is Not a Single Node

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

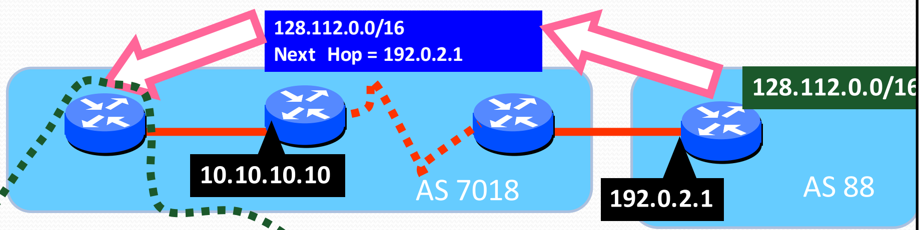


Joining BGP and IGP Information

- Border Gateway Protocol (BGP)
  - Announces reachability to external destinations
  - 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 10.10.10.10



Joining BGP with IGP Information



Forwarding Table

destination	next hop
192.0.2.0/30	10.10.10.10

+

BGP

destination	next hop
128.112.0.0/16	192.0.2.1

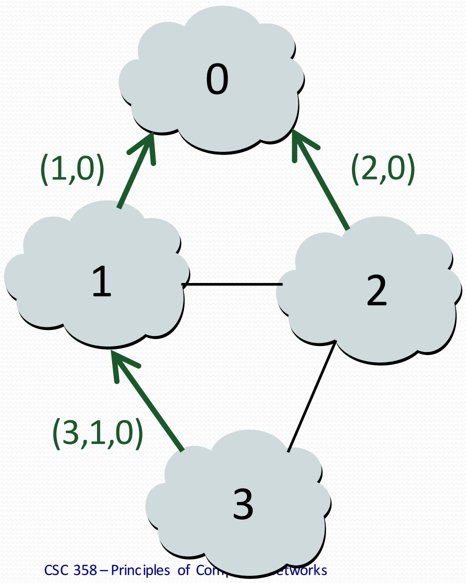
Forwarding Table

destination	next hop
128.112.0.0/16	10.10.10.10
192.0.2.0/30	10.10.10.10

Causes of BGP Routing Changes

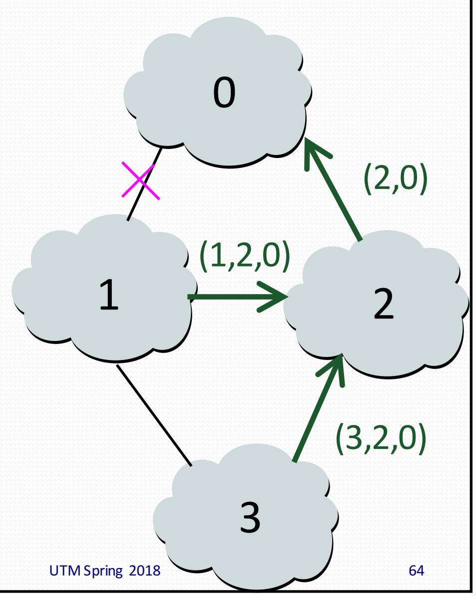
- Topology changes
  - Equipment going up or down
  - Deployment of new routers or sessions
- BGP session failures
  - Due to equipment failures, maintenance, etc.
  - Or, due to congestion on the physical path
- Changes in routing policy
  - Reconfiguration of preferences
  - Reconfiguration of route filters
- Persistent protocol oscillation
  - Conflicts between policies in different AS's

Routing Change: Before and After



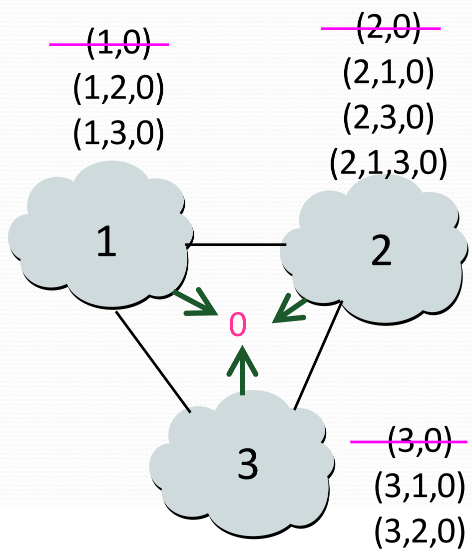
Routing Change: Path Exploration

- AS 1
  - Delete the route (1,0)
  - Switch to next route (1,2,0)
  - Send route (1,2,0) to AS 3
- AS 3
  - Sees (1,2,0) replace (1,0)
  - Compares to route (2,0)
  - Switches to using AS 2



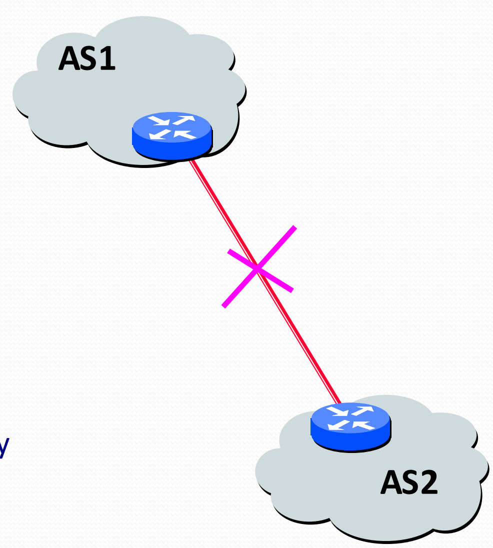
Routing Change: Path Exploration

- Initial situation
  - Destination 0 is alive
  - All AS's use direct path
- When destination dies
  - All AS's lose direct path
  - All switch to longer paths
  - Eventually withdrawn
- E.g., AS 2
  - (2,0) → (2,1,0)
  - (2,1,0) → (2,3,0)
  - (2,3,0) → (2,1,3,0)
  - (2,1,3,0) → null



BGP Session Failure

- BGP runs over TCP
  - BGP only sends updates when changes occur
  - TCP doesn't detect lost connectivity on its own
- Detecting a failure
  - Keep-alive: 60 seconds
  - Hold timer: 180 seconds
- Reacting to a failure
  - Discard all routes learned from the neighbor
  - Send new updates for any routes that change



BGP Converges Slowly, if at All

- Path vector avoids count-to-infinity
  - But, AS's still must explore many alternate paths
  - … to find the highest-ranked path that is still available
- Fortunately, in practice
  - Most popular destinations have very stable BGP routes
  - And most instability lies in a few unpopular destinations
- Still, lower BGP convergence delay is a goal
  - Can be tens of seconds to tens of minutes
  - High for important interactive applications
  - … or even conventional application, like Web browsing

Conclusions

- BGP is solving a hard problem
  - Routing protocol operating at a global scale
  - With tens of thousands of independent networks
  - That each have their own policy goals
  - And all want fast convergence
- Key features of BGP
  - Prefix-based path-vector protocol
  - Incremental updates (announcements and withdrawals)
  - Policies applied at import and export of routes
  - Internal BGP to distribute information within an AS
  - Interaction with the IGP to compute forwarding tables