CSC 458/2209 – Computer Networks

Handout # 9:

Internet Topology and Routing

Instructed by:

Joe Lim – L5101

joe.lim@utoronto.ca

Sajad Shirali-Shahreza – L0201

shirali@cs.toronto.edu

AbdulAziz AlHelali – L0101

a.alhelali@mail.utoronto.ca

Slides adapted from

Professor Yashar Ganjali

Announcements

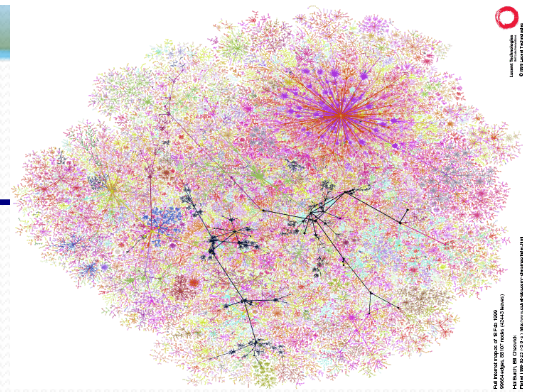
- Don't forget the programming assignment.
  - Due: Sunday Oct. 22 at 11:59pm.
  - Take advantage of tutorials, and TA office hours.
  - Don't leave it to the last minute.
  - Submit electronically on MarkUs.
- Midterm: Tuesday October 17th 6:00 – 8:00PM
  - For all sections
  - Location: TBA
  - For undergraduate and graduate students
- Reading for this week: Chapter 4

Outline

- Internet's Topology
  - Internet's two-tiered topology
  - AS-level topology   AS: autonomous system
  - Router-level topology

- Routing in the Internet
  - Hierarchy and Autonomous Systems
  - Interior Routing Protocols: RIP, OSPF
  - Exterior Routing Protocol: BGP

Internet Routing Architecture



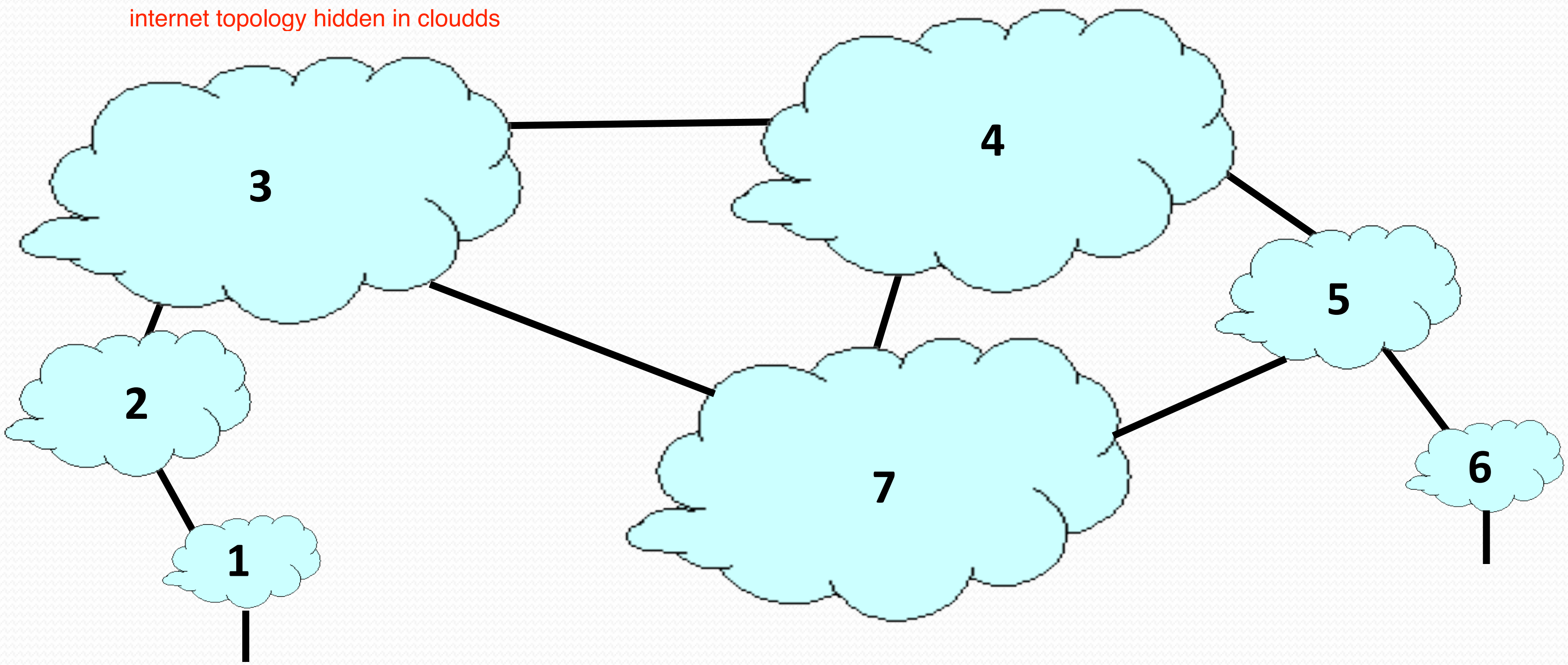
- Divided into Autonomous Systems
  - Distinct regions of administrative control
  - Routers/links managed by a single "institution"
  - Service provider, company, university, …
- Hierarchy of Autonomous Systems
  - Large, tier-1 provider with a nationwide backbone
  - Medium-sized regional provider 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

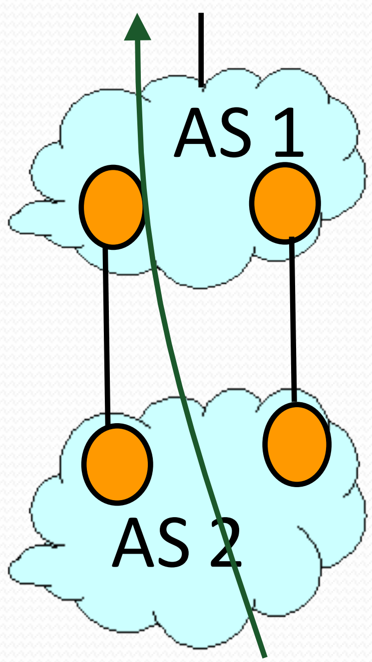
Do no know how many router links the 2 AS

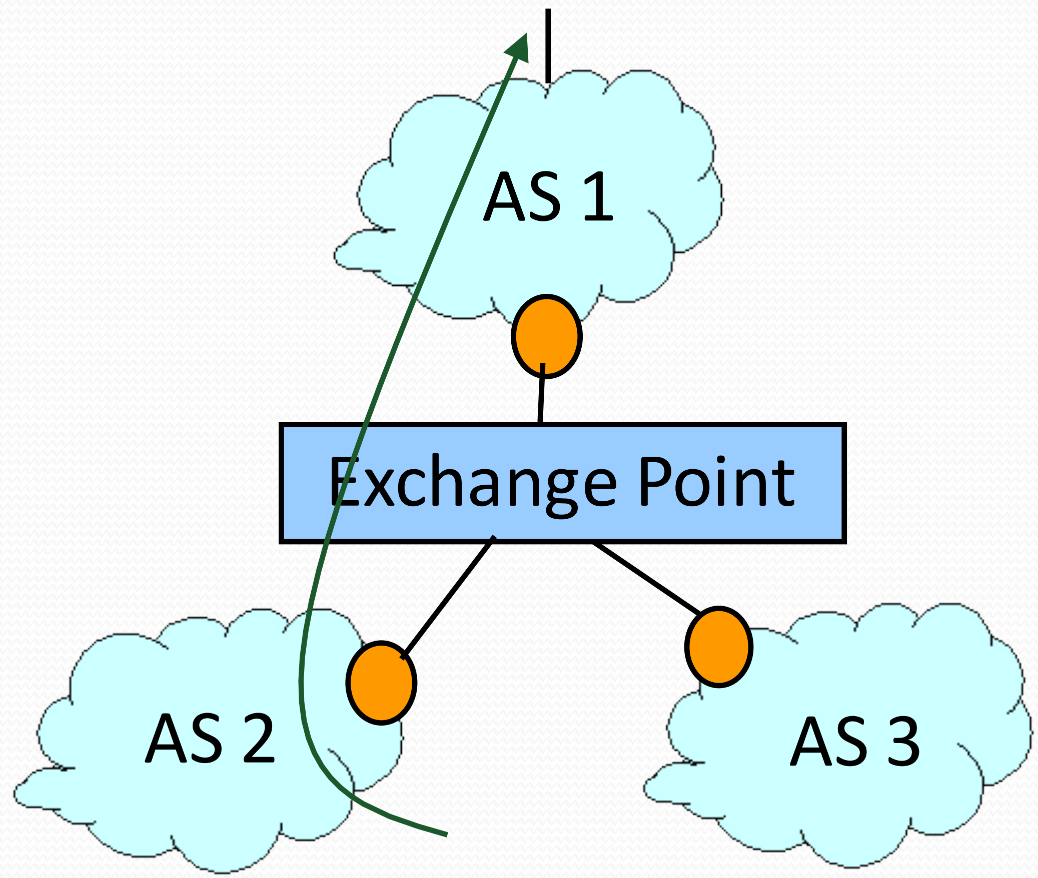
internet topology hidden in cloudds



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





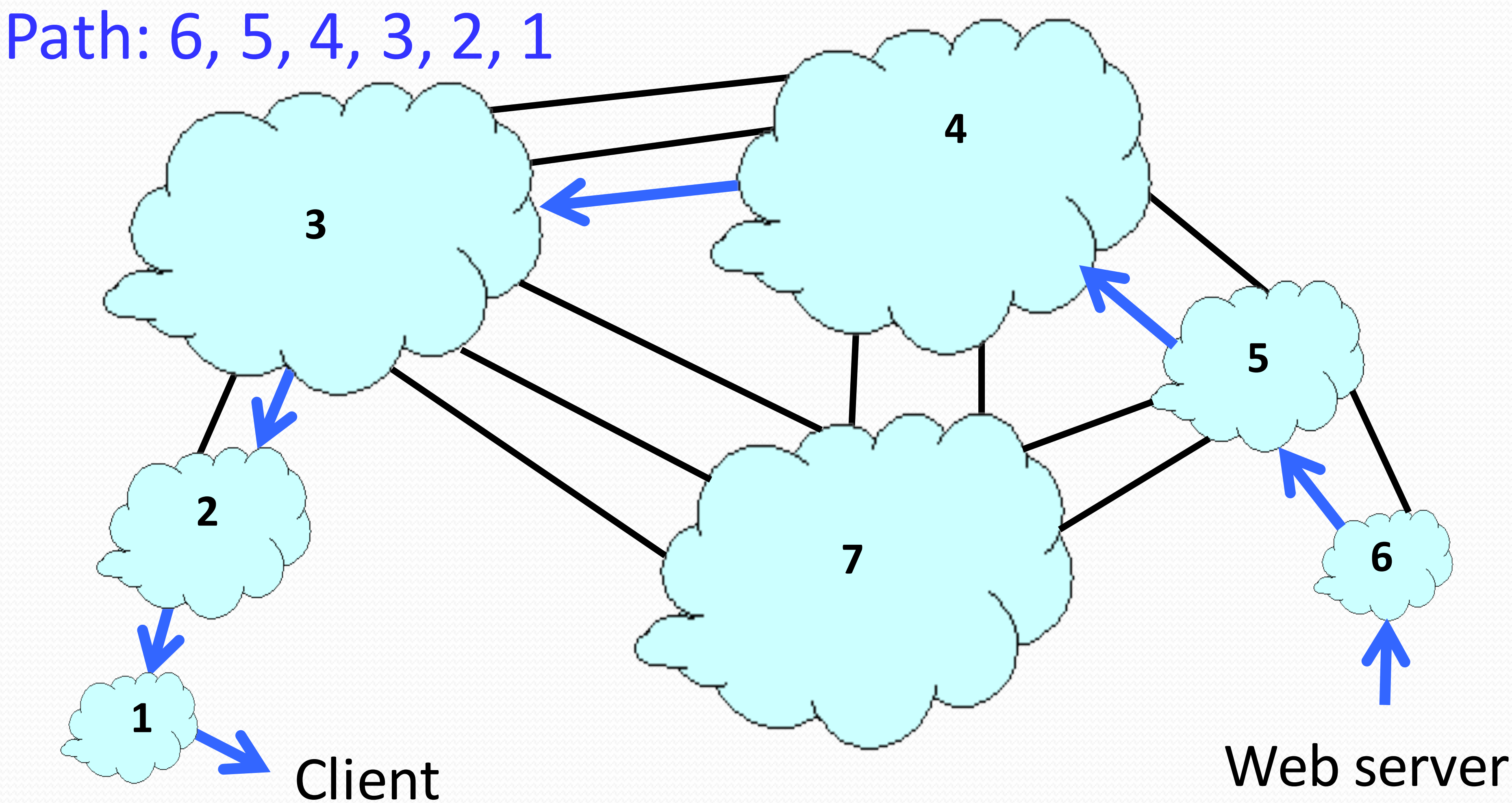
Identifying Autonomous Systems

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

Currently just over 54,000 in use.

- **Level 3: 1** level 3 is a company
- **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

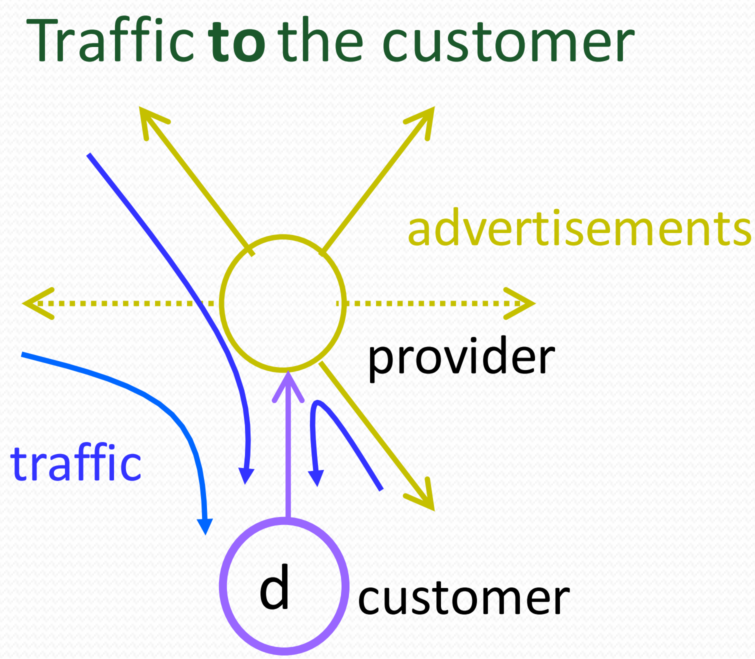


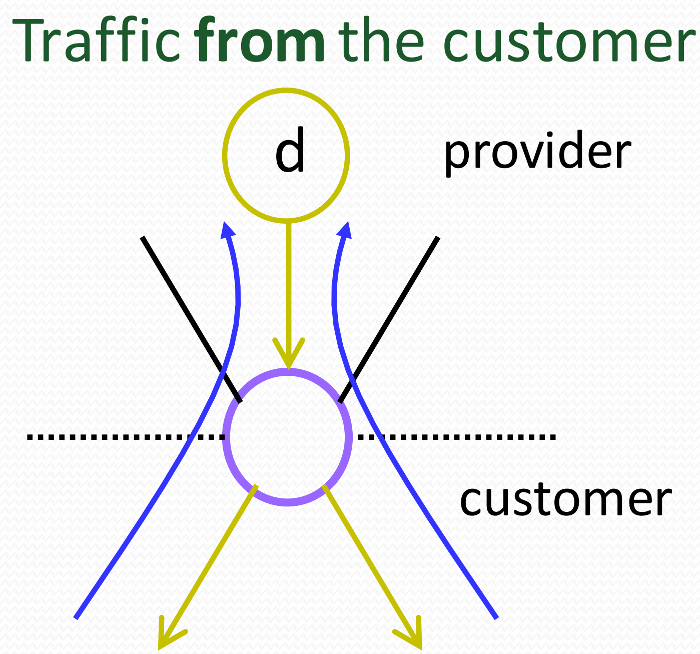
Business Relationships

- 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 customer provider from tier 2 -> tier 1 cost money
    - E.g., Princeton is a customer of AT&T
    - E.g., MIT is a customer of Level 3
  - Peer-peer p2p is free of charge
    - 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

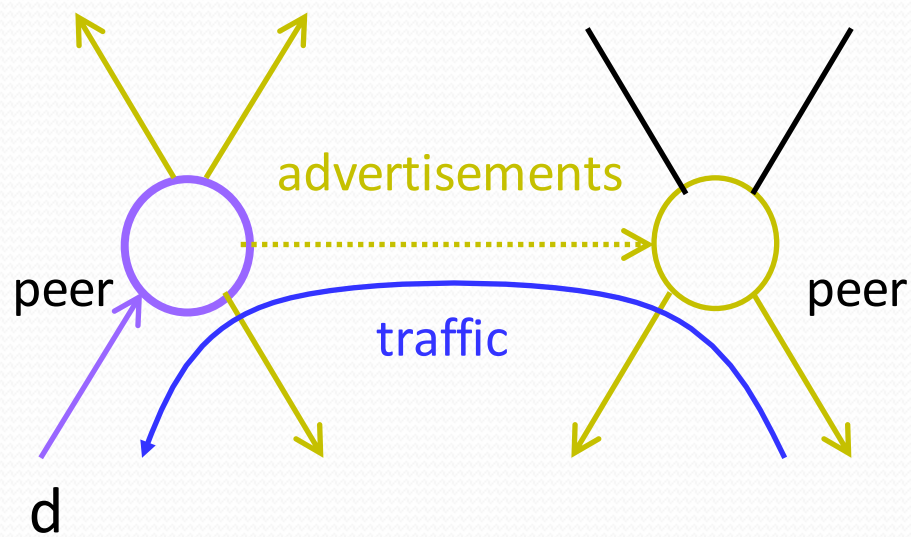




Peer-Peer Relationship

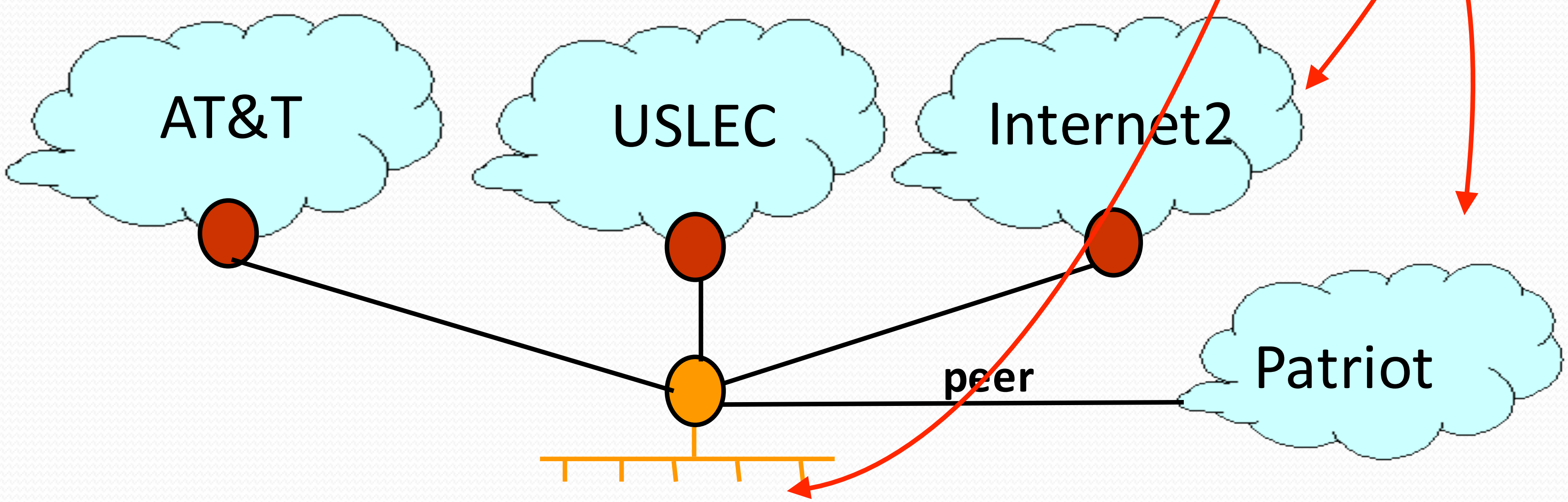
- Peers exchange traffic between customers
  - AS exports only customer routes to a peer
  - AS exports a peer’s routes only to its customers
  - Often the relationship is settlement-free (i.e., no $$$)

Traffic to/from the peer and its customers



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

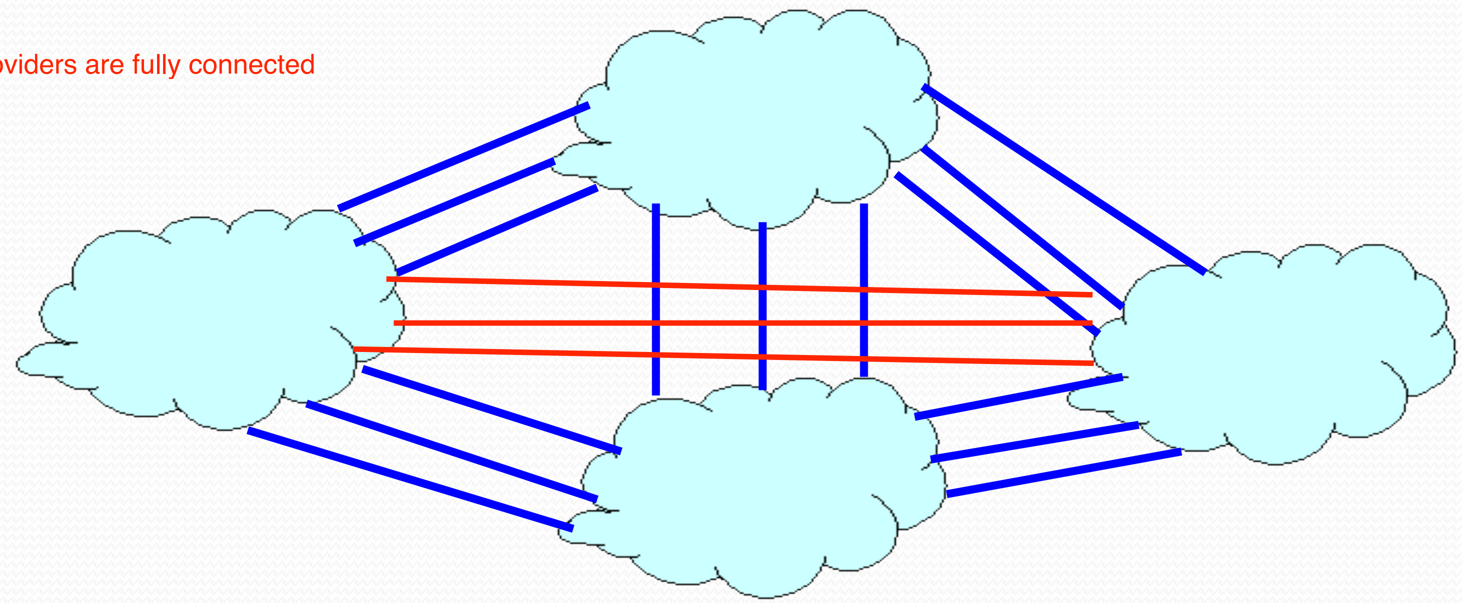


AS Structure: Tier-1 Providers

- 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

access to long llinks

tier1 providers are fully connected

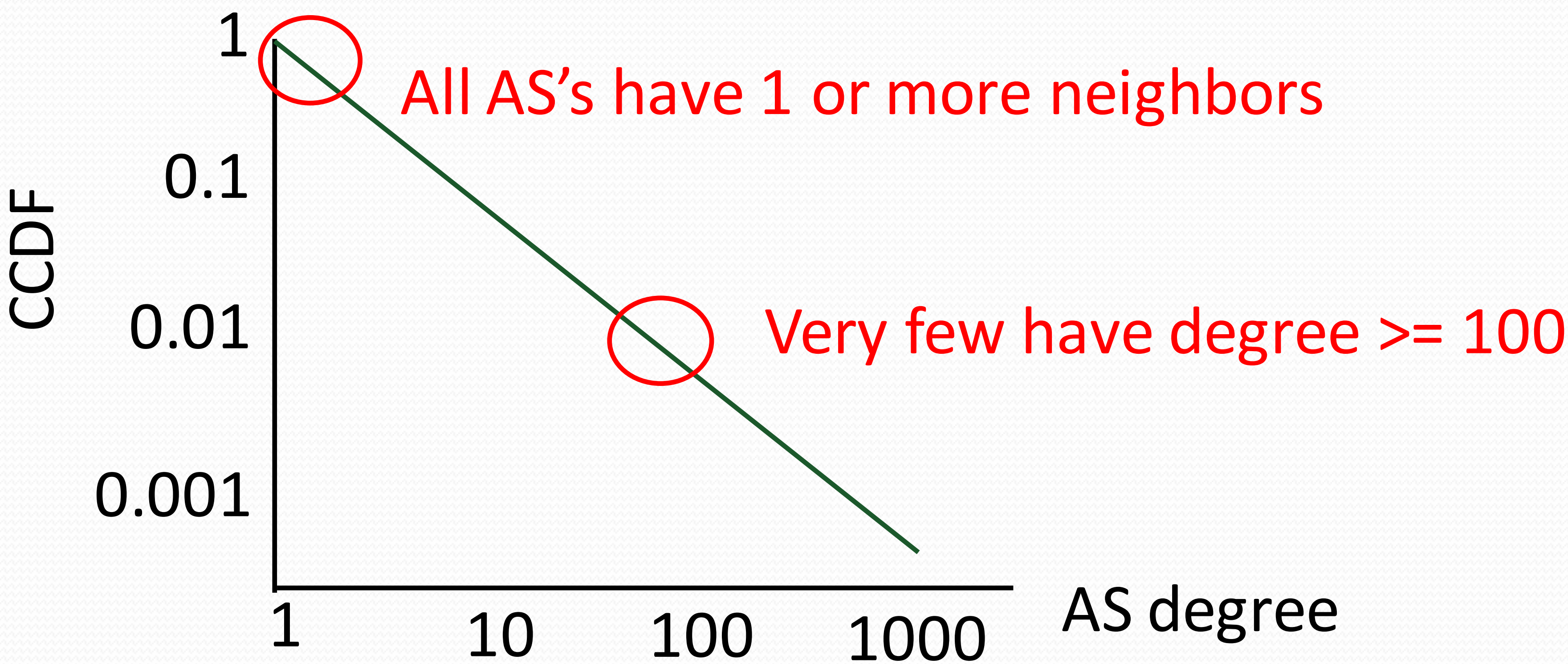


AS Structure: Other AS's

- Tier-2 providers bell roger…
  - 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 the leafs
  - 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

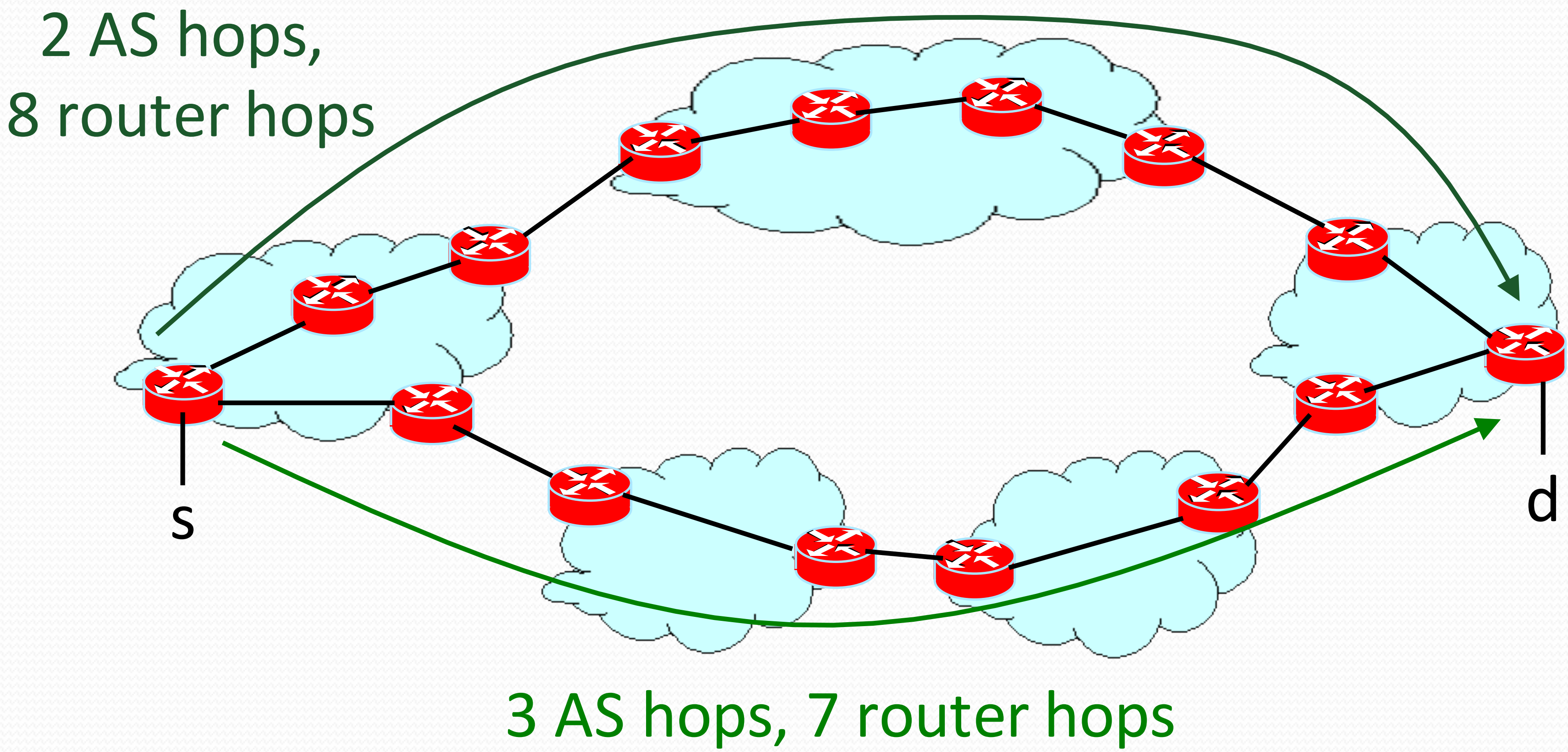
Characteristics of the AS Graph

- AS graph structure
  - High variability in node degree ("power law")
  - A few very highly-connected AS's tier1
  - Many AS's have only a few connections stubs



Characteristics of AS Paths

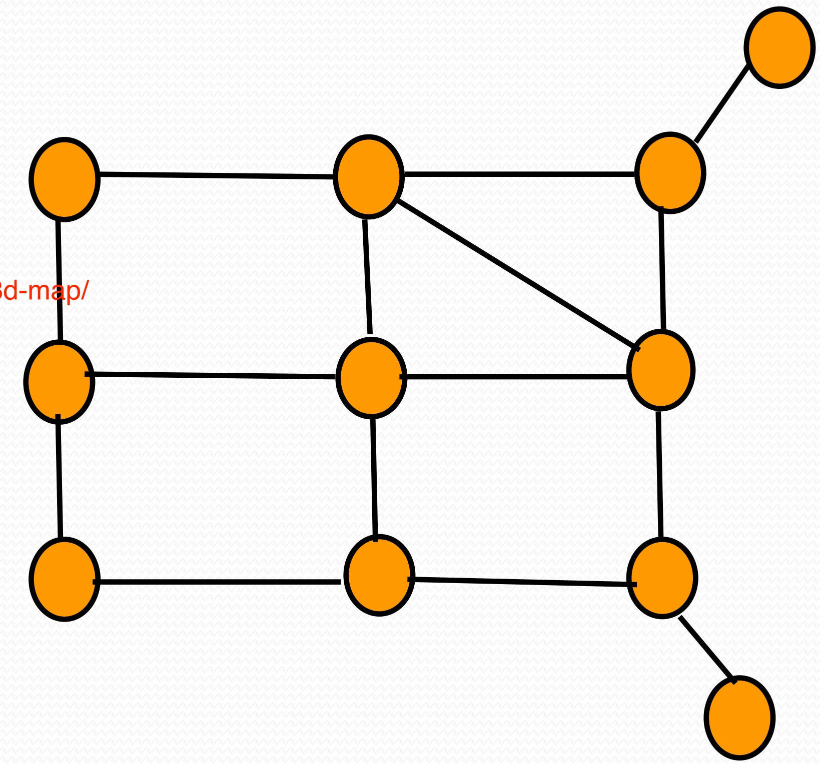
- AS path may be longer than shortest AS path
- Router path may be longer than shortest path



Backbone Networks

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

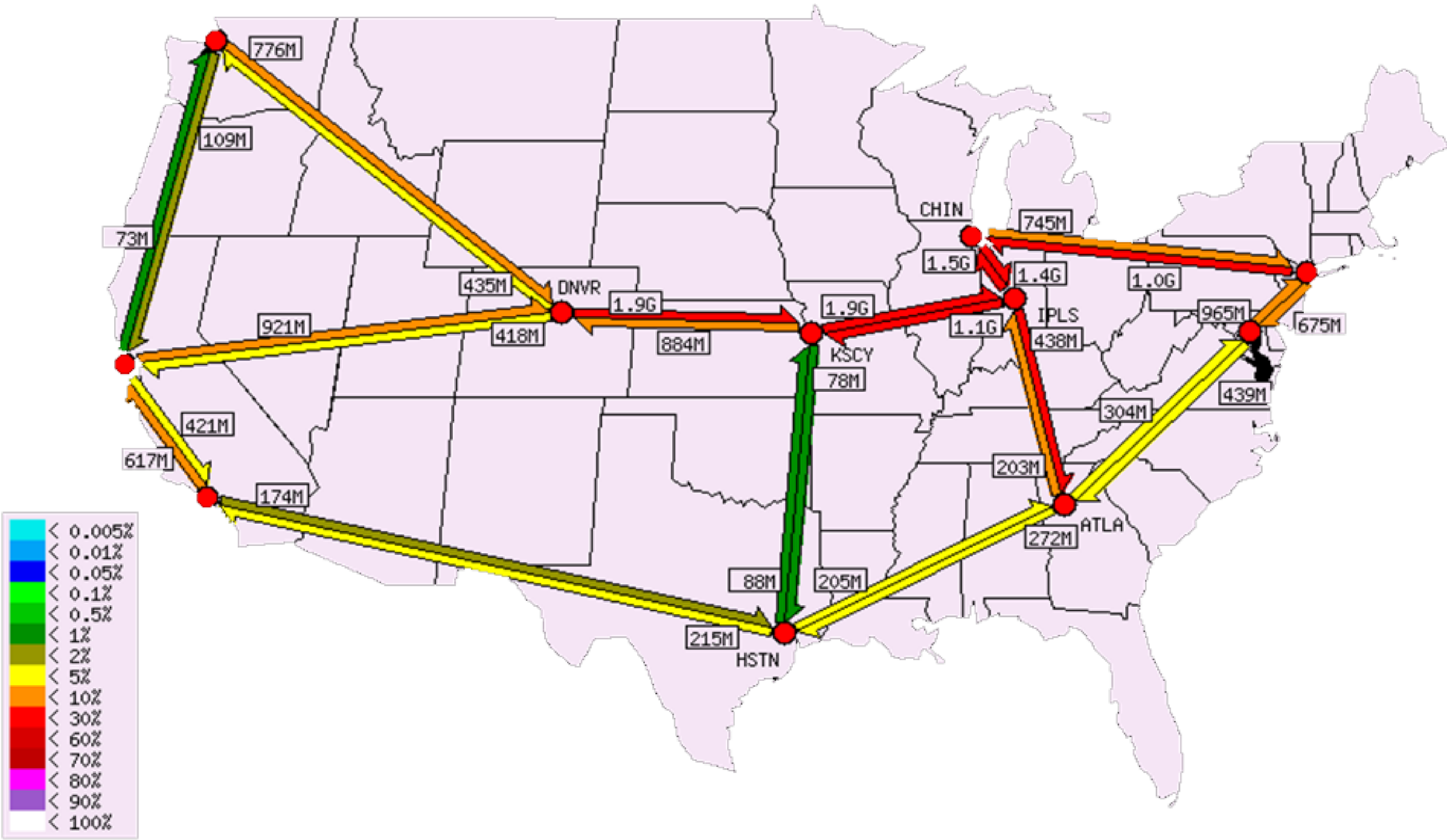
http://he.net/3d-map/



usually on a global scale

internet2, connects universities in US

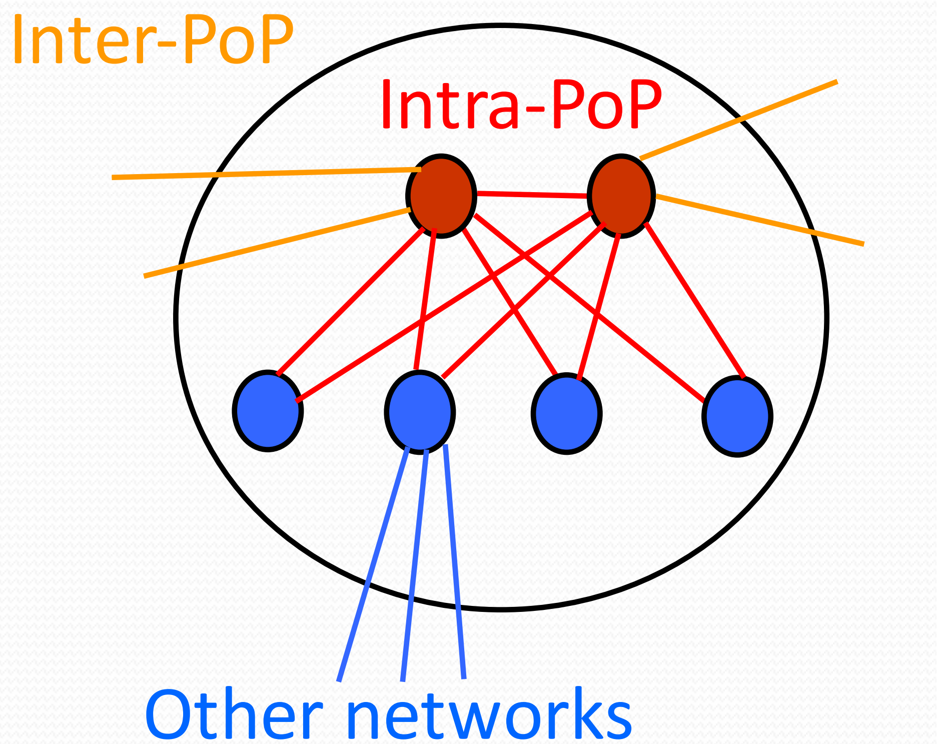
Example: Abilene Internet2 Backbone



PoP, a location for long distance carrier to provide service to local networks

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

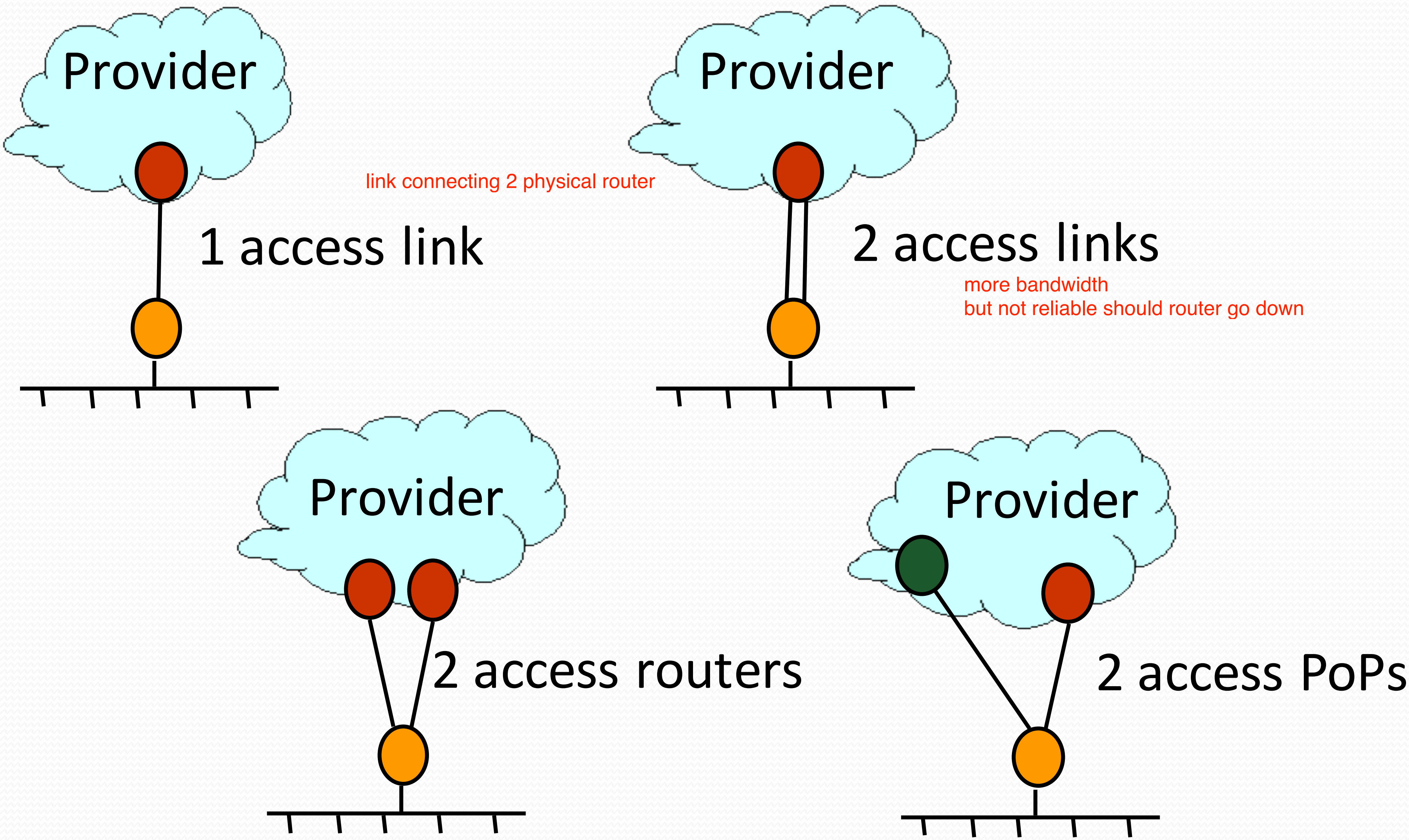


Where to Locate Nodes and Links

- 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

PoPs:
an artificial demarcation point or interface point between communicating entities.
usually a data center housing numerous routers, switches, … equipments

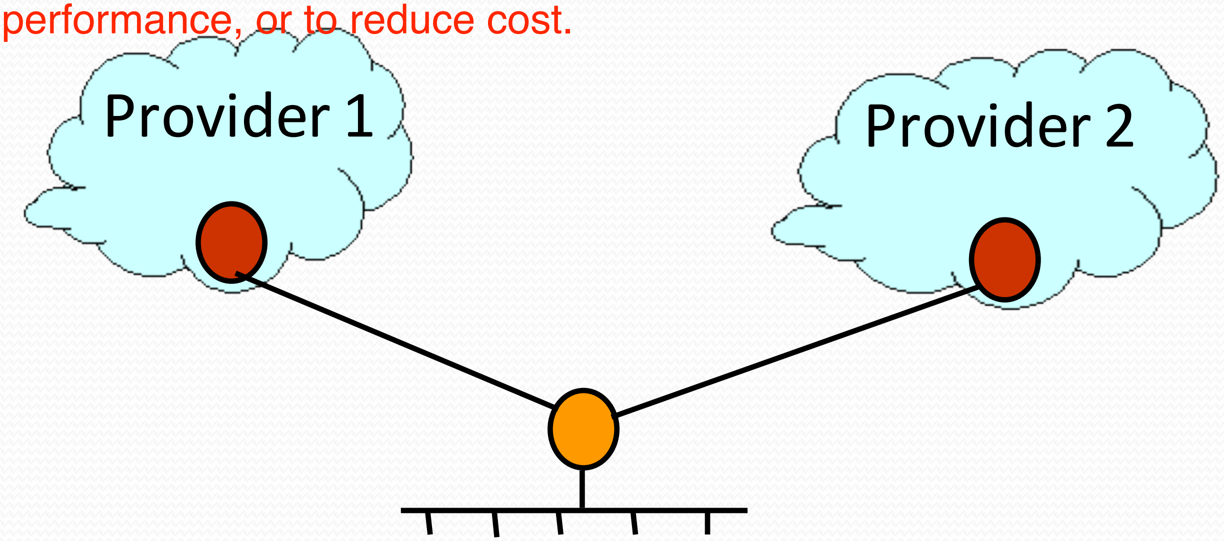
Customer Connecting to a Provider



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

Multihoming is the practice of connecting a host or a computer network to more than one network. This can be done in order to increase reliability or performance, or to reduce cost.



Want to know what AS between client and host

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

Map Traceroute Hops to AS's

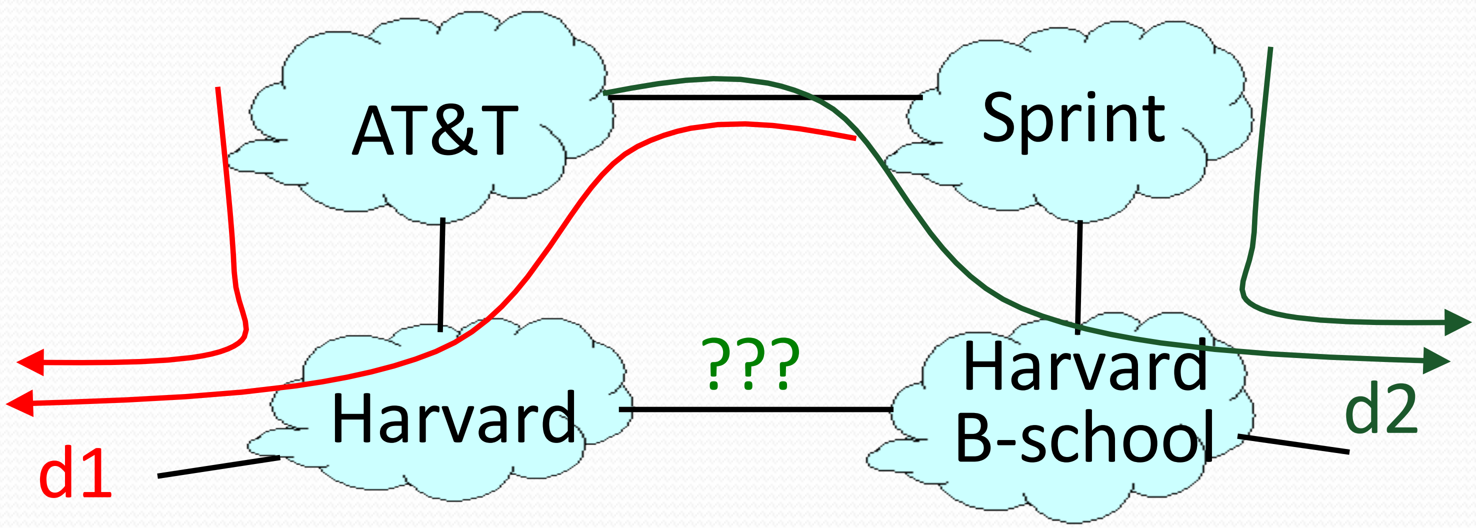
Traceroute output: (hop number, IP)

Hop	IP	AS	Network
1	169.229.62.1	AS25	Berkeley
2	169.229.59.225	AS25	Berkeley
3	128.32.255.169	AS25	Berkeley
4	128.32.0.249	AS25	Berkeley
5	128.32.0.66	AS11423	Calren
6	209.247.159.109	AS3356	Level3
7	*	AS3356	Level3
8	64.159.1.46	AS3356	Level3
9	209.247.9.170	AS3356	Level3
10	66.185.138.33	AS1668	AOL
11	*	AS1668	AOL
12	66.185.136.17	AS1668	AOL
13	64.236.16.52	AS5662	CNN

peer relation are sometimes hidden

Challenges of Inter-AS Mapping

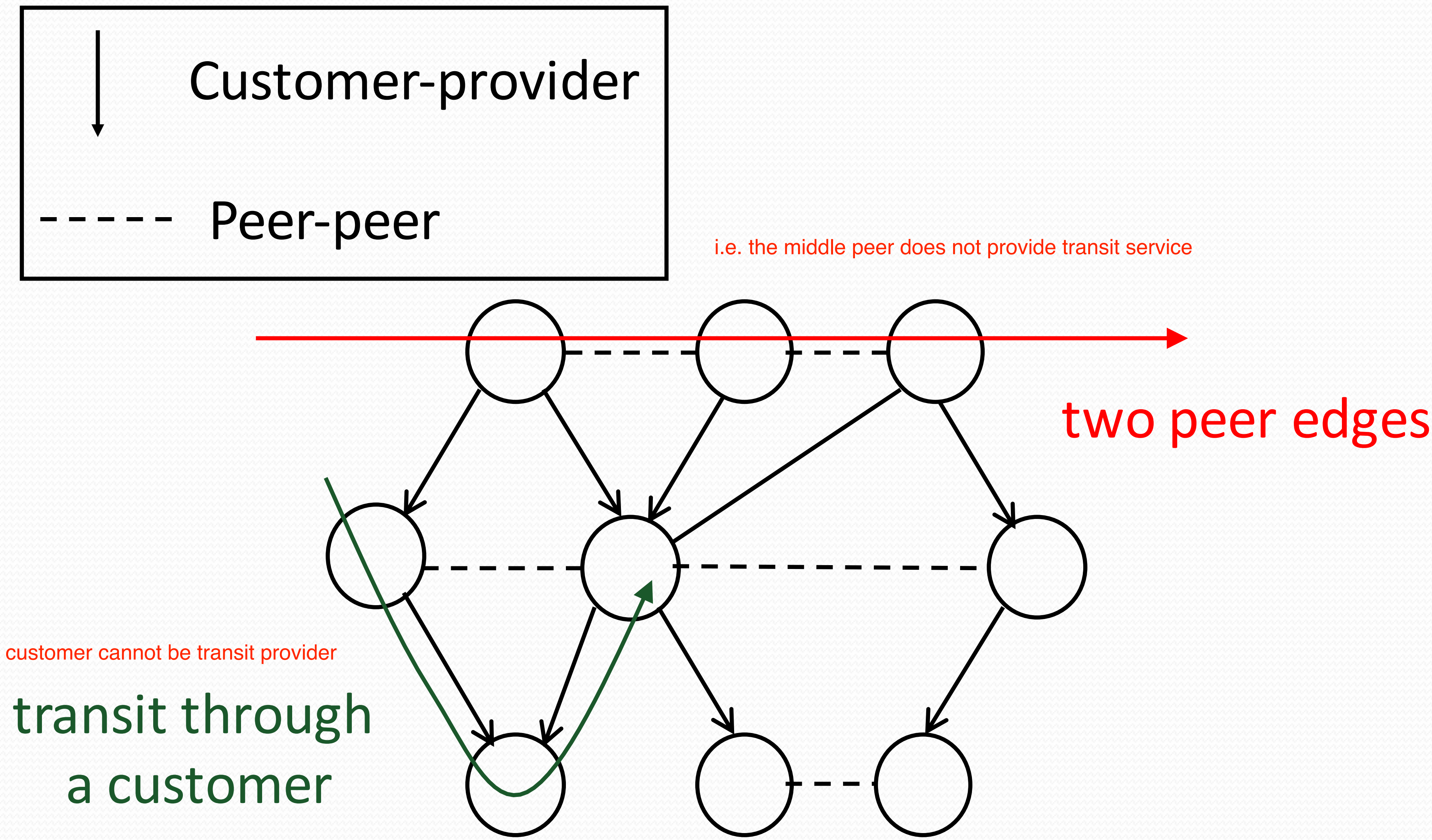
- Mapping traceroute hops to AS's is hard
  - Need an accurate registry of IP address ownership
  - Whois data are notoriously out of date
- Collecting diverse interdomain data is hard
  - Public repositories like RouteViews and RIPE-RIS
  - Covers hundreds to thousands of vantage points
  - Especially hard to see peer-peer edges



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

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

Routing Story So Far …

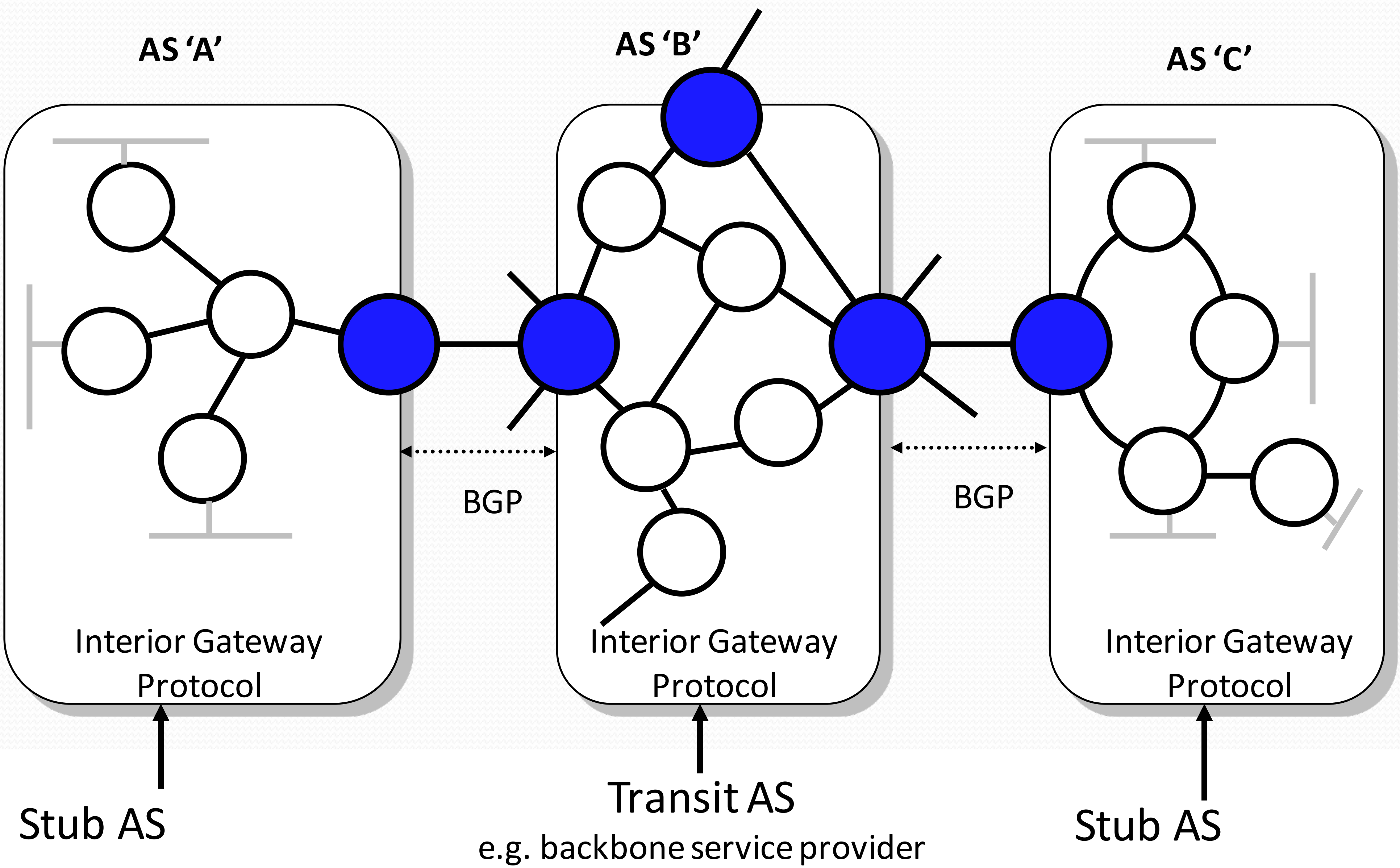
- Techniques
  - Flooding
  - Distributed Bellman Ford Algorithm
  - Dijkstra's Shortest Path First Algorithm

- 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, ISIS (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

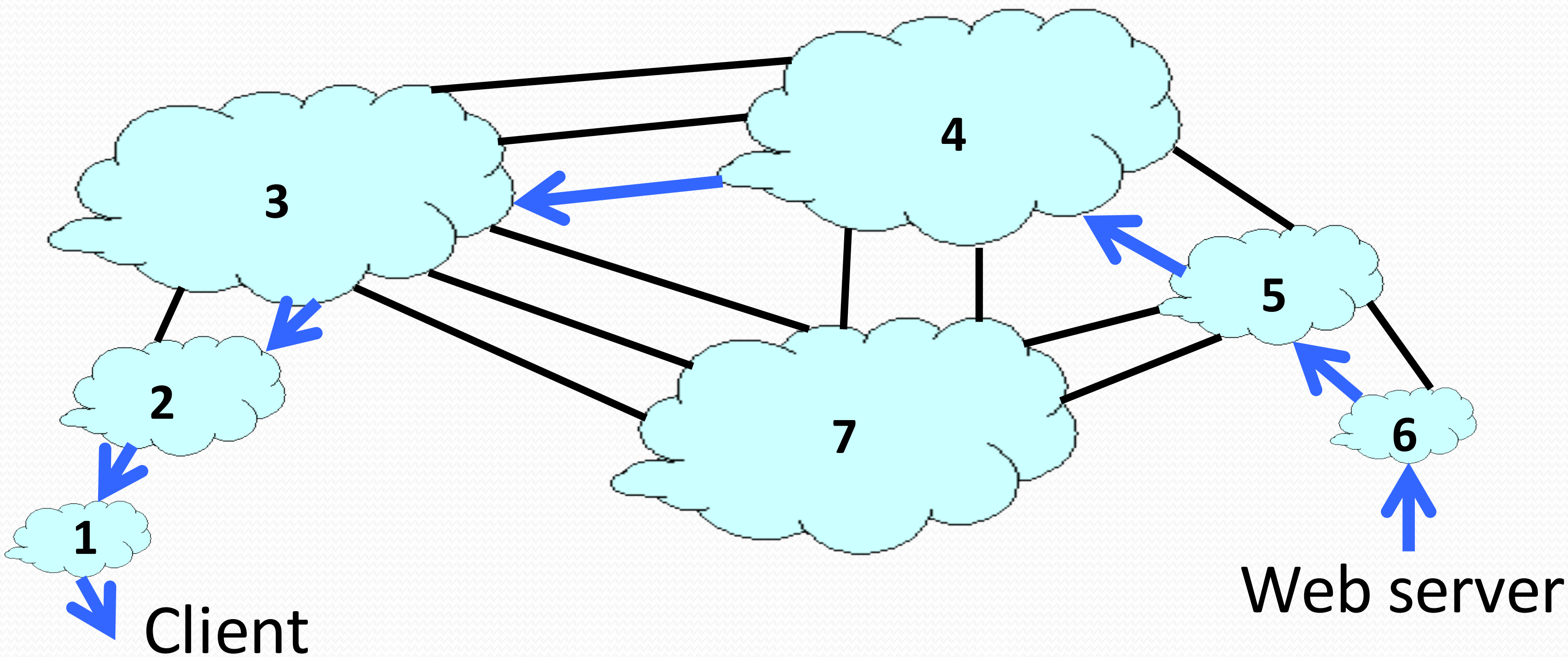


Interior Routing Protocols

- RIP
  - 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
  - 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

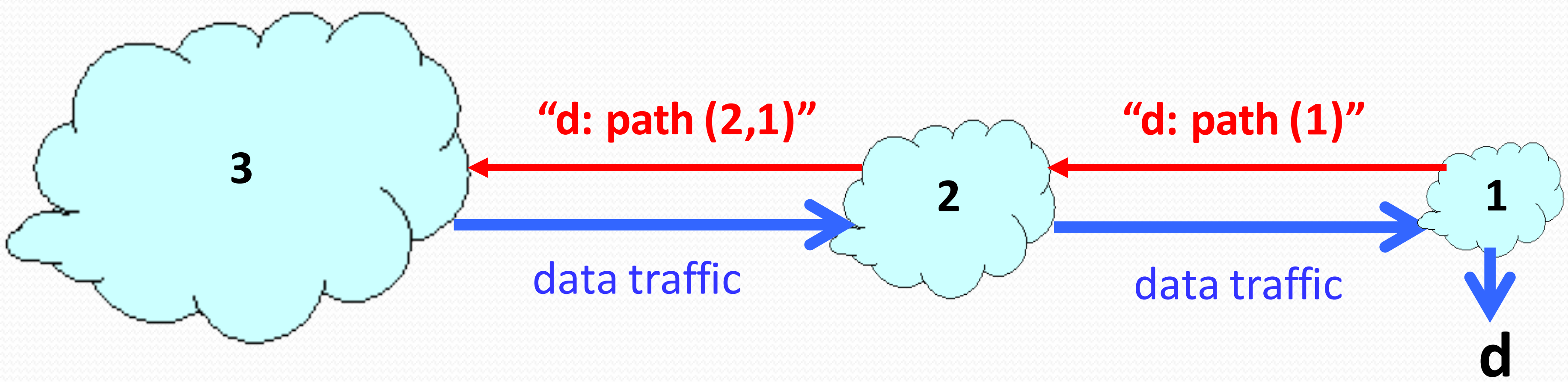
- Topology information is flooded
  - High bandwidth and storage overhead
  - Forces nodes to divulge sensitive information
- Entire path computed locally per node
  - High processing overhead in a large network
- Minimizes some notion of total distance
  - Works only if policy is shared and uniform
- 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

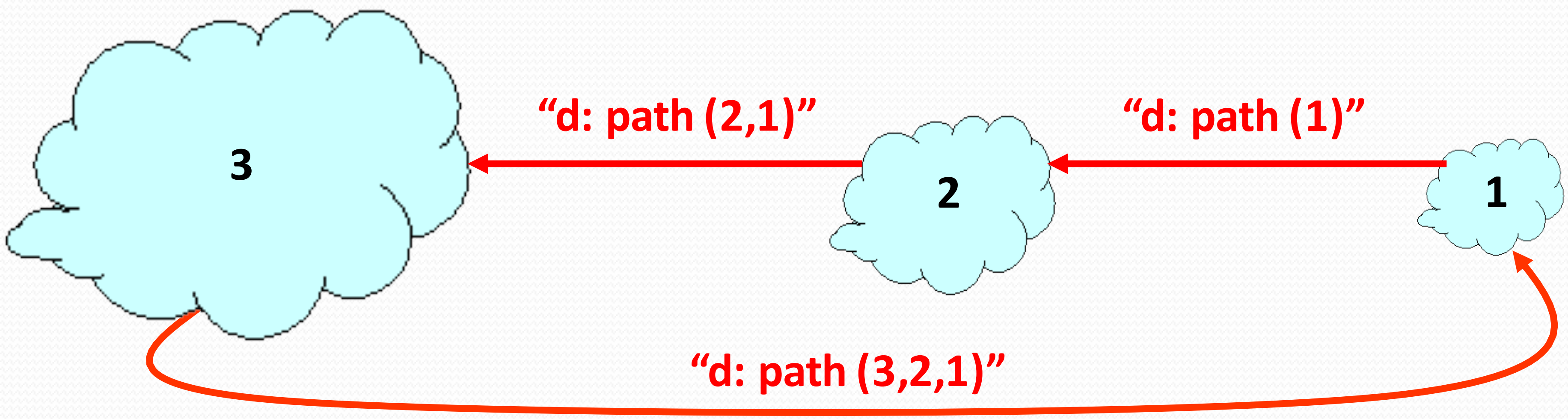
Path-Vector Routing

- 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

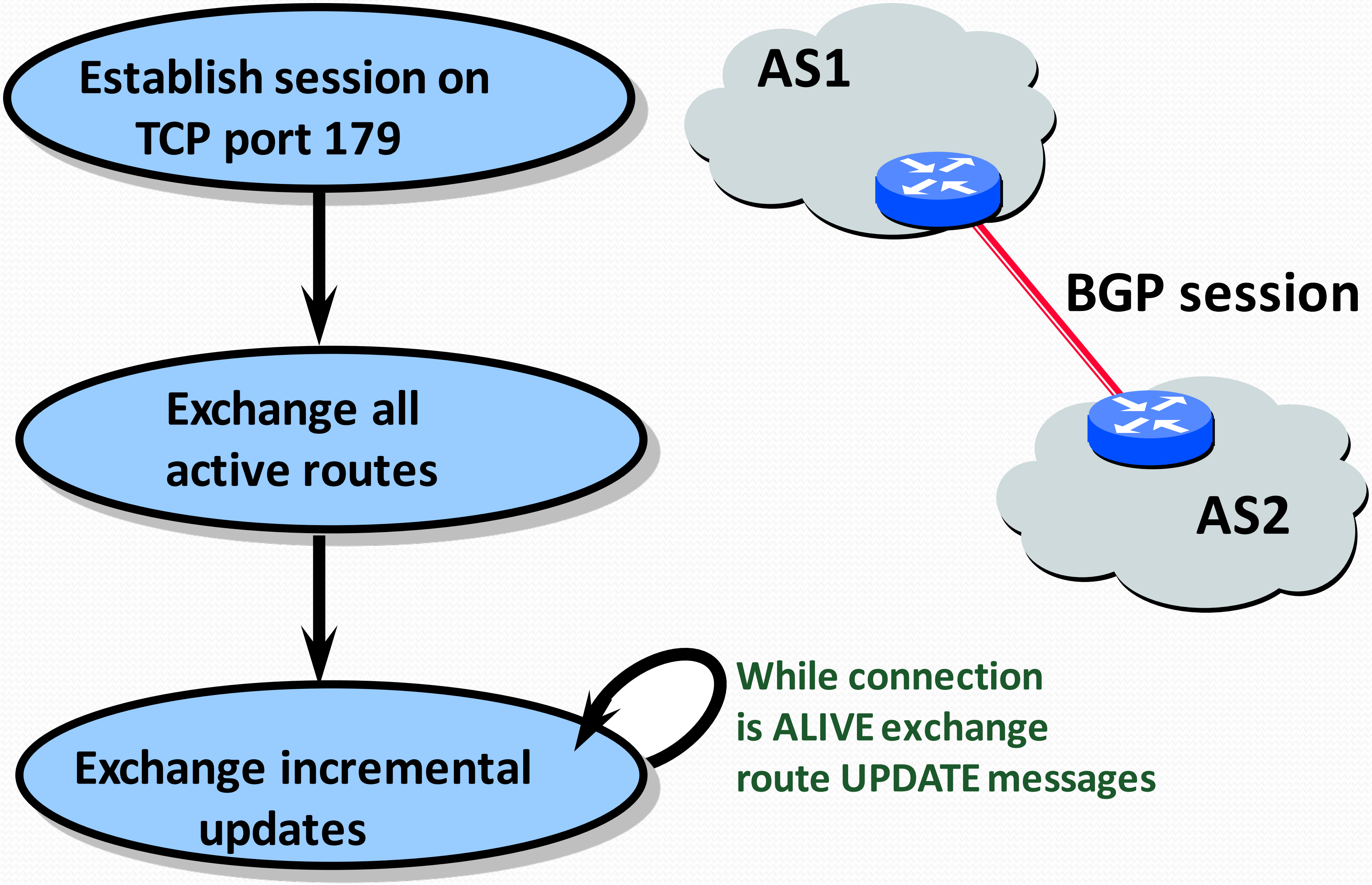
- Node can easily detect a loop
  - Look for its own node identifier in the path
  - E.g., node 1 sees itself in the path “3, 2, 1”
- Node can simply discard paths with loops
  - E.g., node 1 simply discards the advertisement



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 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

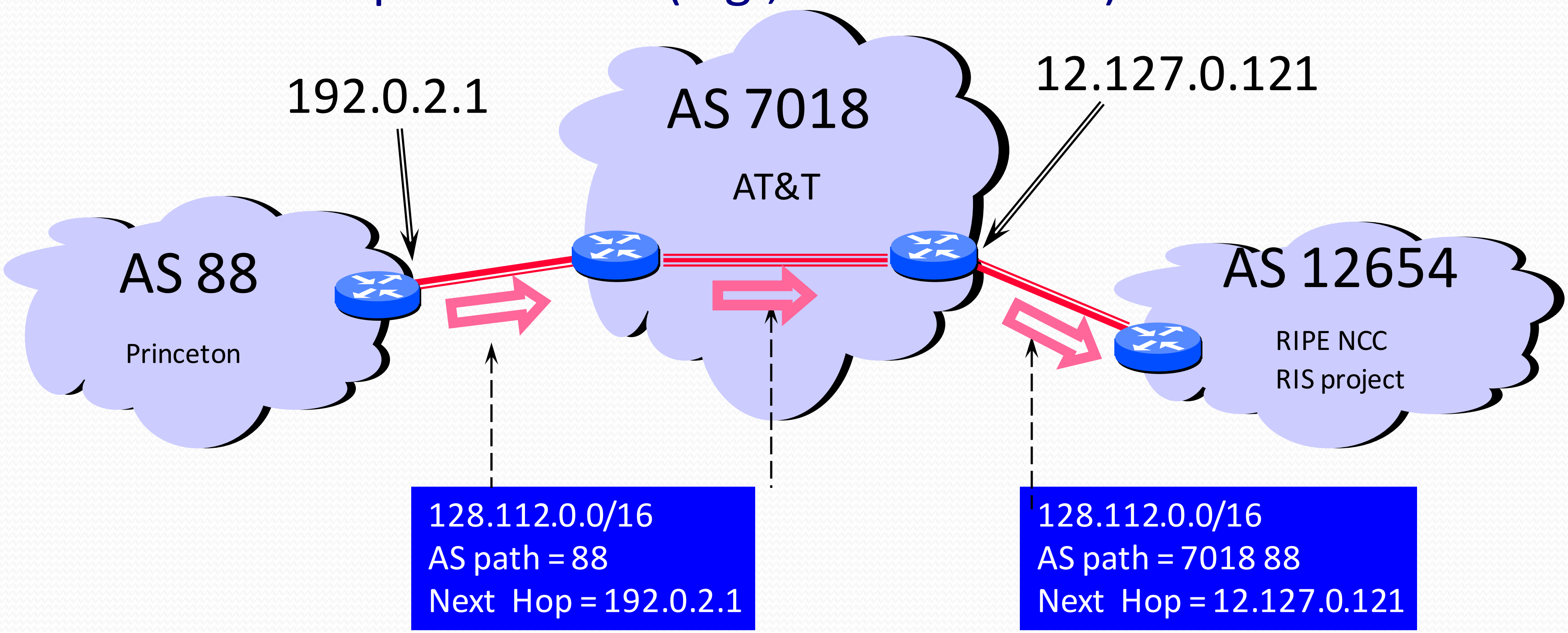
- Open : Establish a BGP session.
- Keep Alive : Handshake at regular intervals.
- Notification : Shuts down a peering session.
- Update : Announcing new routes or withdrawing previously announced routes.

BGP announcement = prefix + path attributes

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

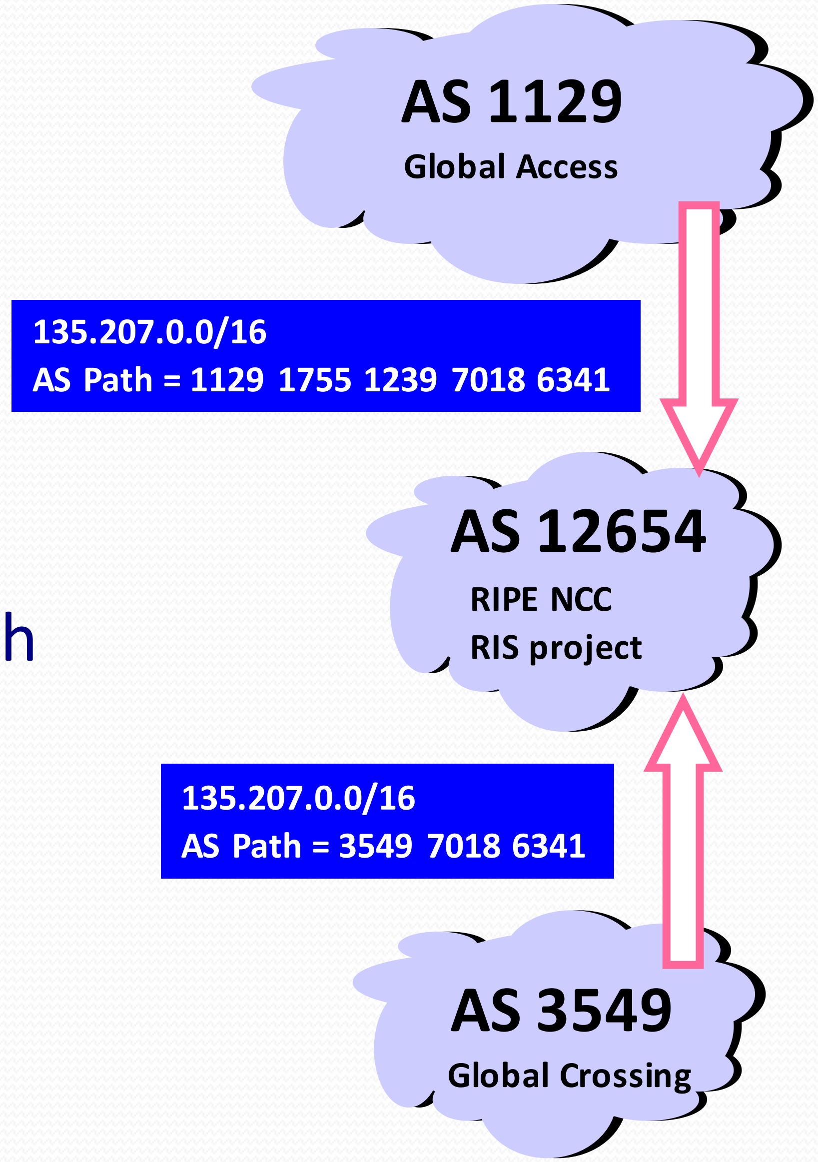
BGP Route

- 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)

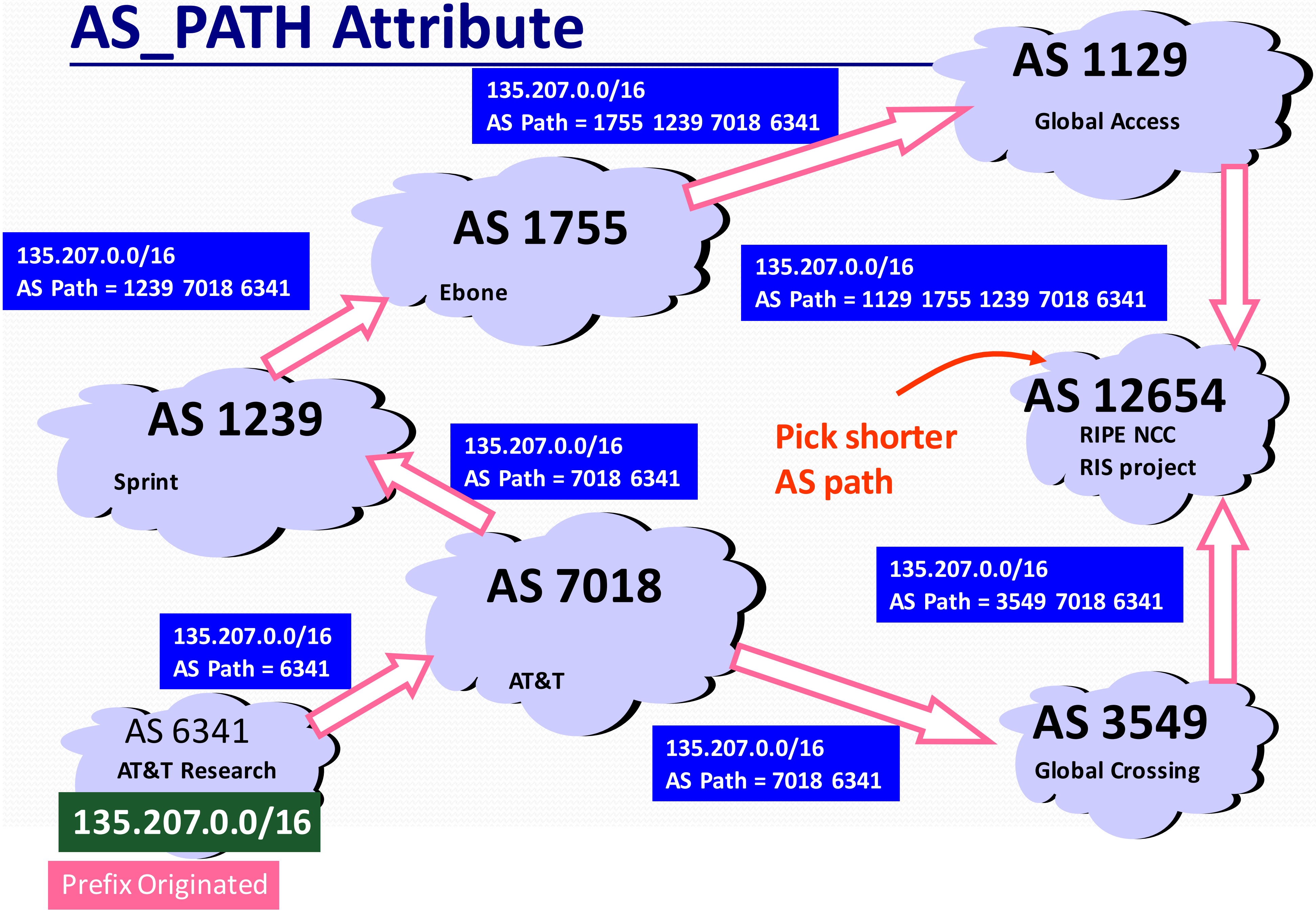


BGP Path Selection

- 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

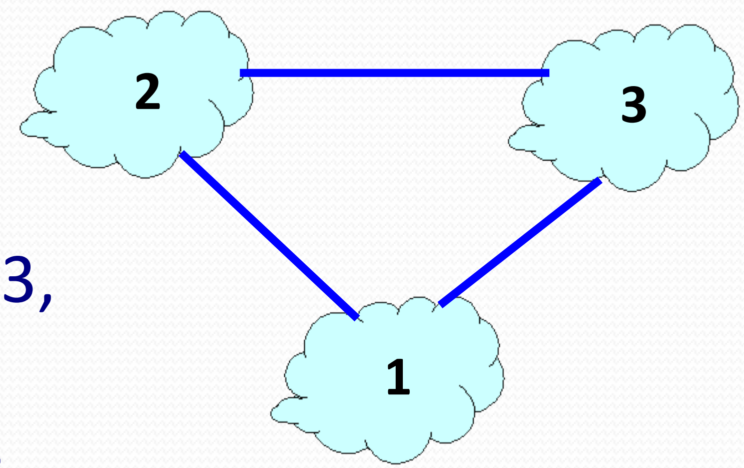


AS_PATH Attribute

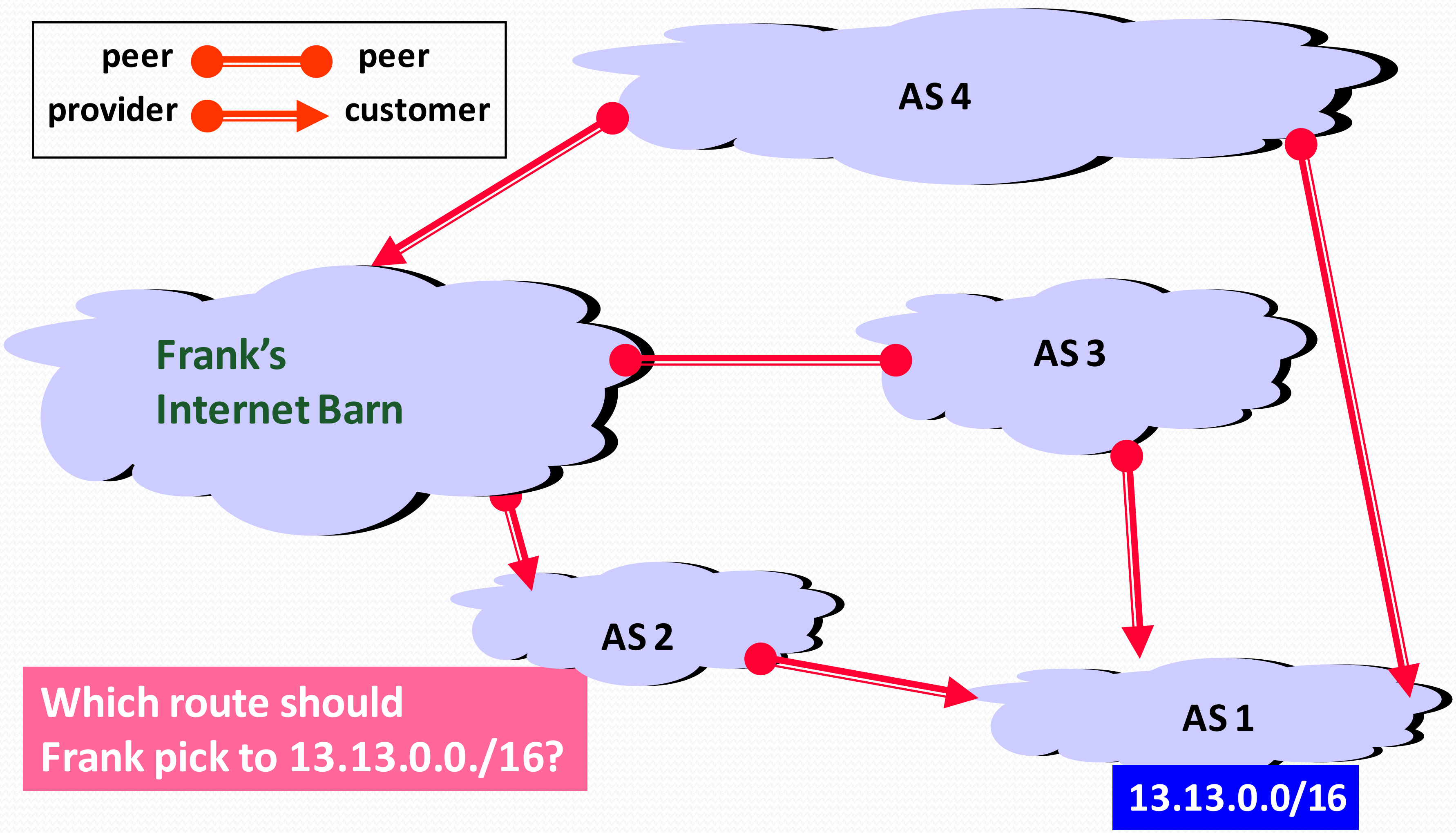


Flexible Policies

- 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”



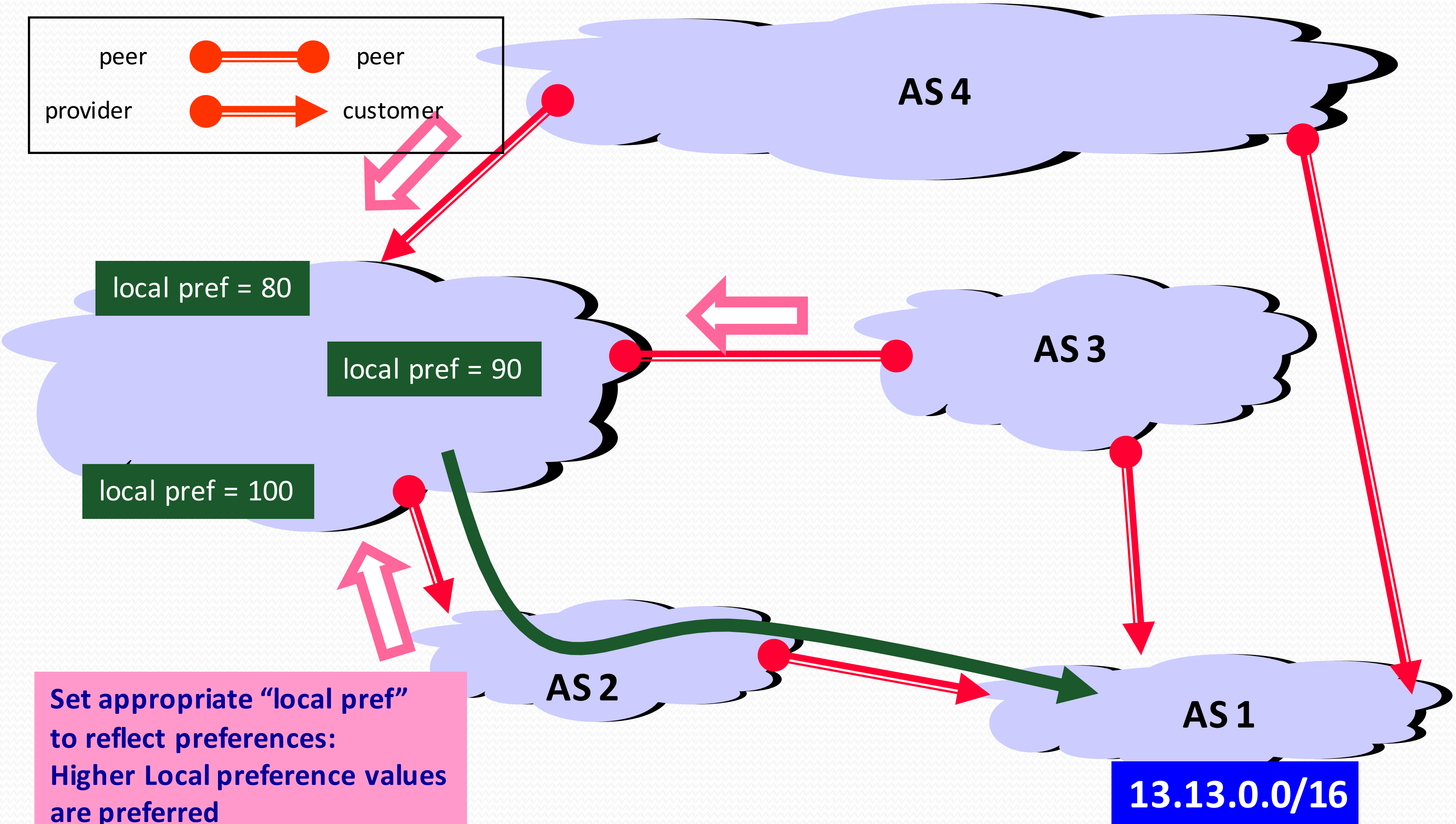
So Many Choices…



Which route should
Frank pick to 13.13.0.0./16?

Frank's Choices…

Route learned from customer preferred over
route learned from peer, preferred over
route learned from provider



Set appropriate "local pref"
to reflect preferences:
Higher Local preference values
are preferred

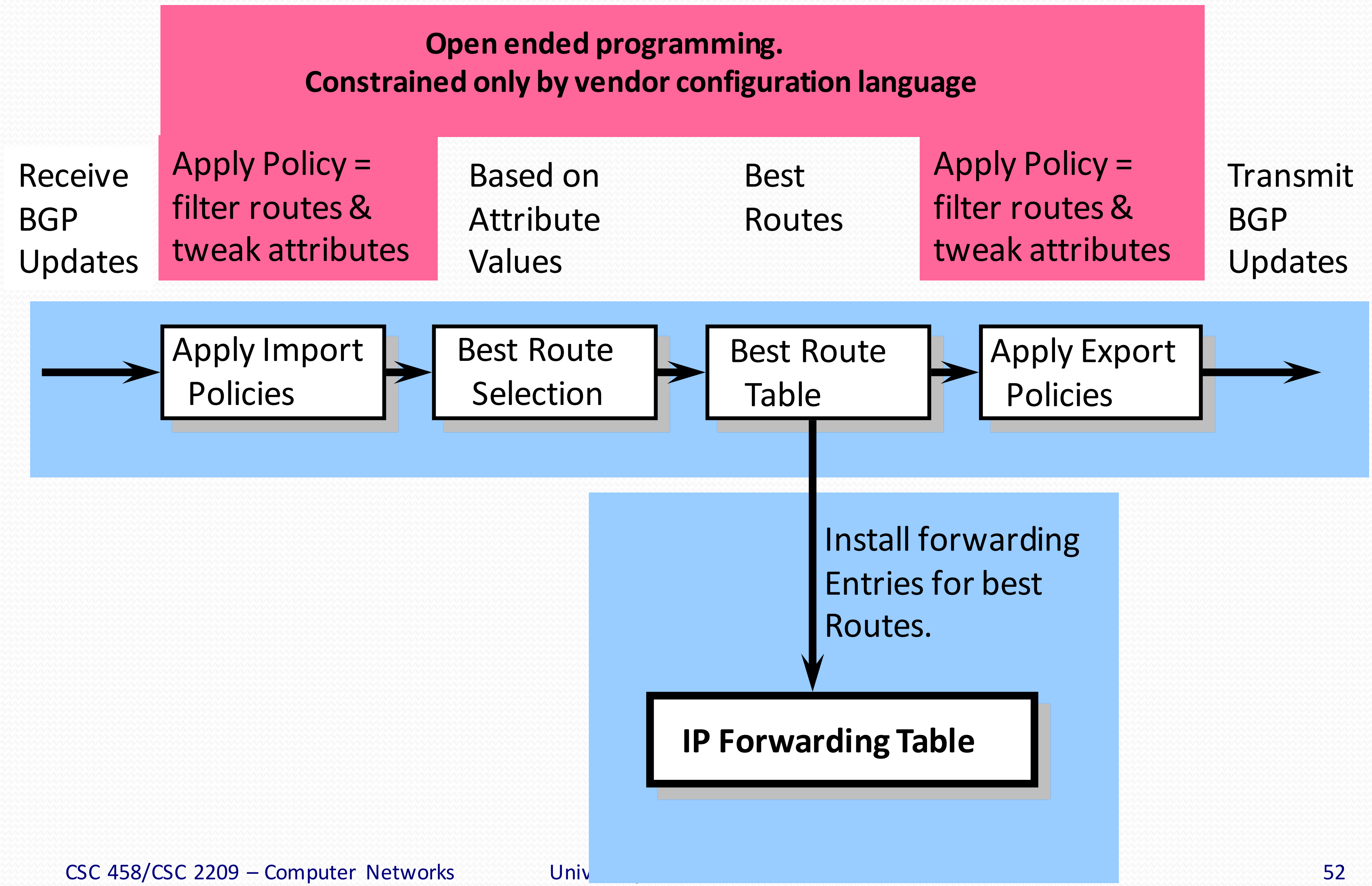
BGP Route Selection Summary

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

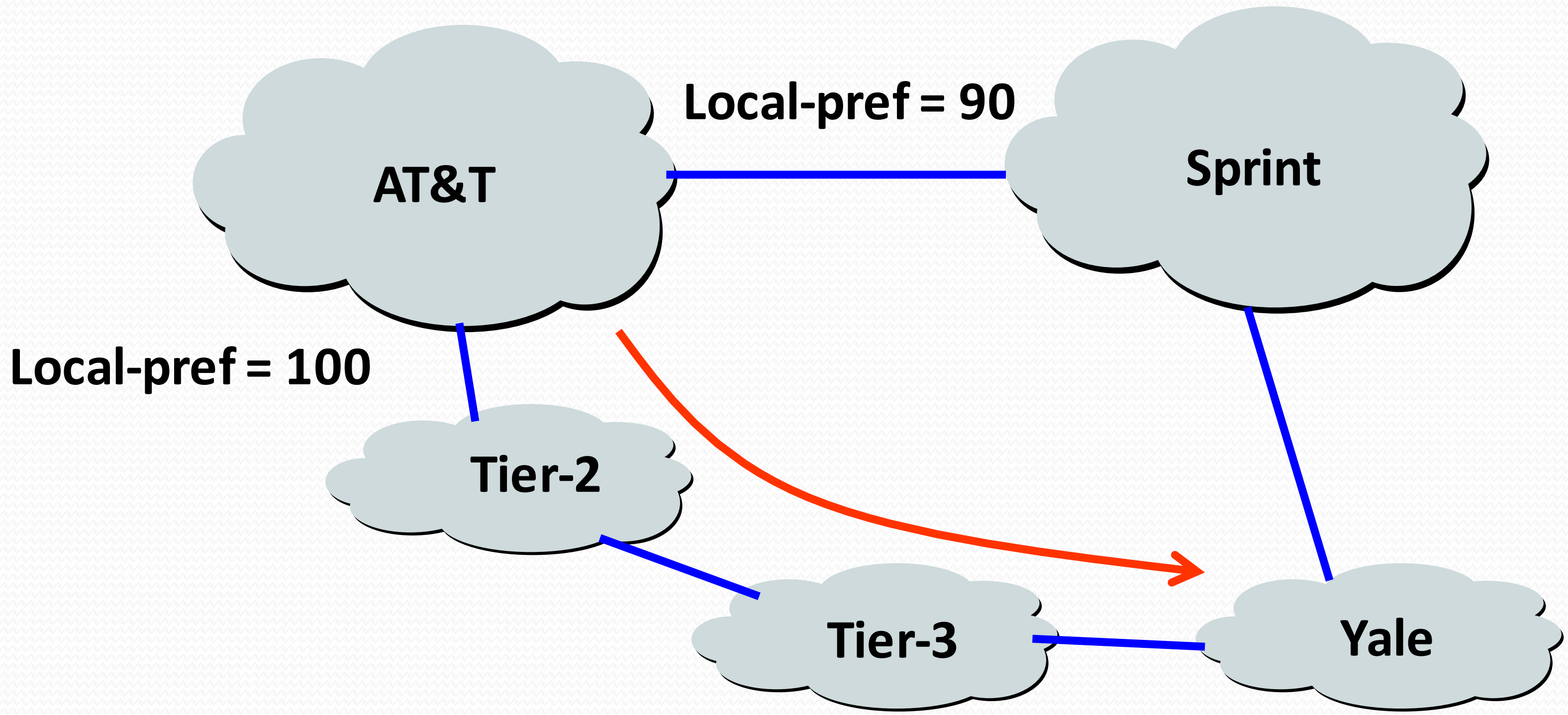
- Import policy
  - Filter unwanted routes from neighbor
    - E.g. prefix that your customer doesn't own
  - Manipulate attributes to influence path selection
    - E.g., assign local preference to favored routes
- Export policy
  - Filter routes you don't want to tell your neighbor
    - E.g., don't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



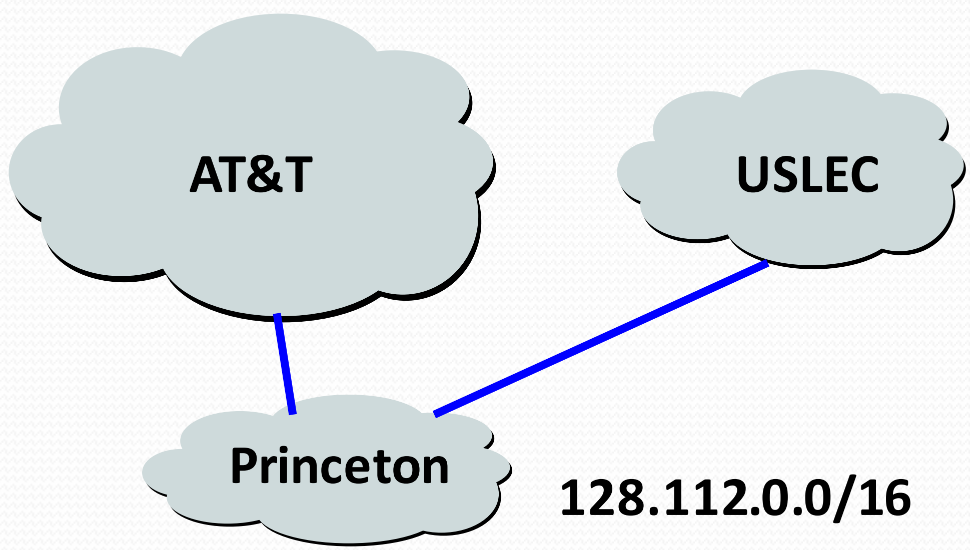
Import Policy: Local Preference

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



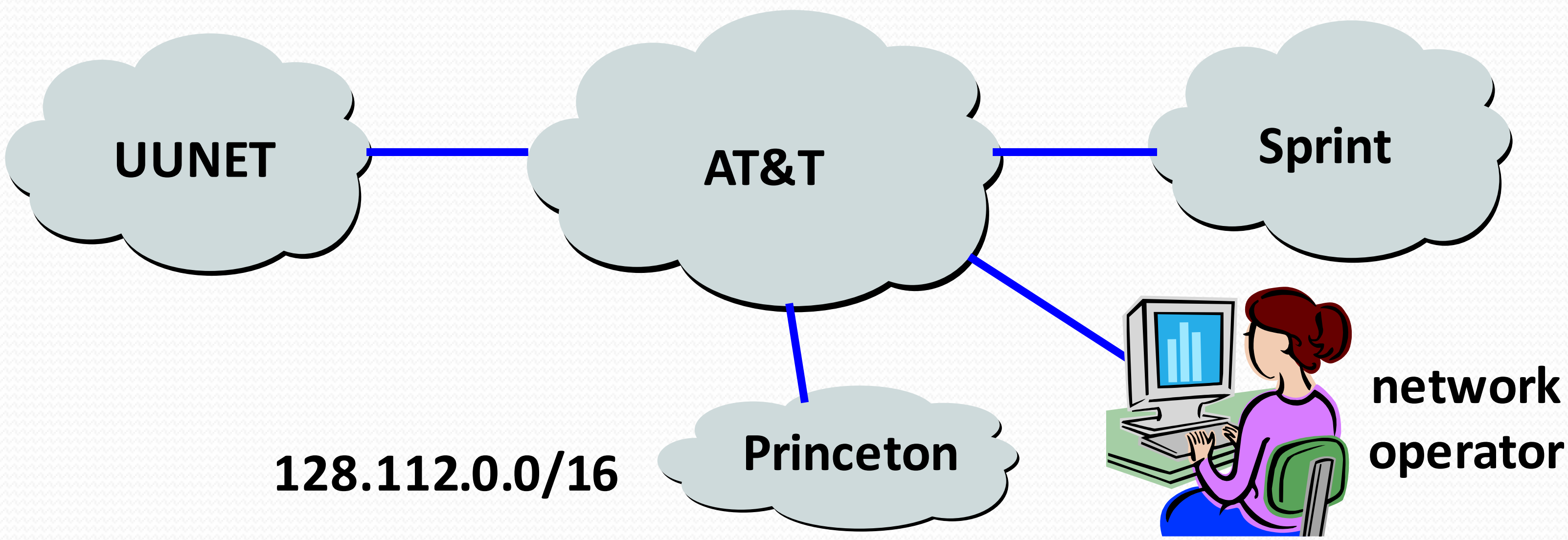
Import Policy: Filtering

- 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



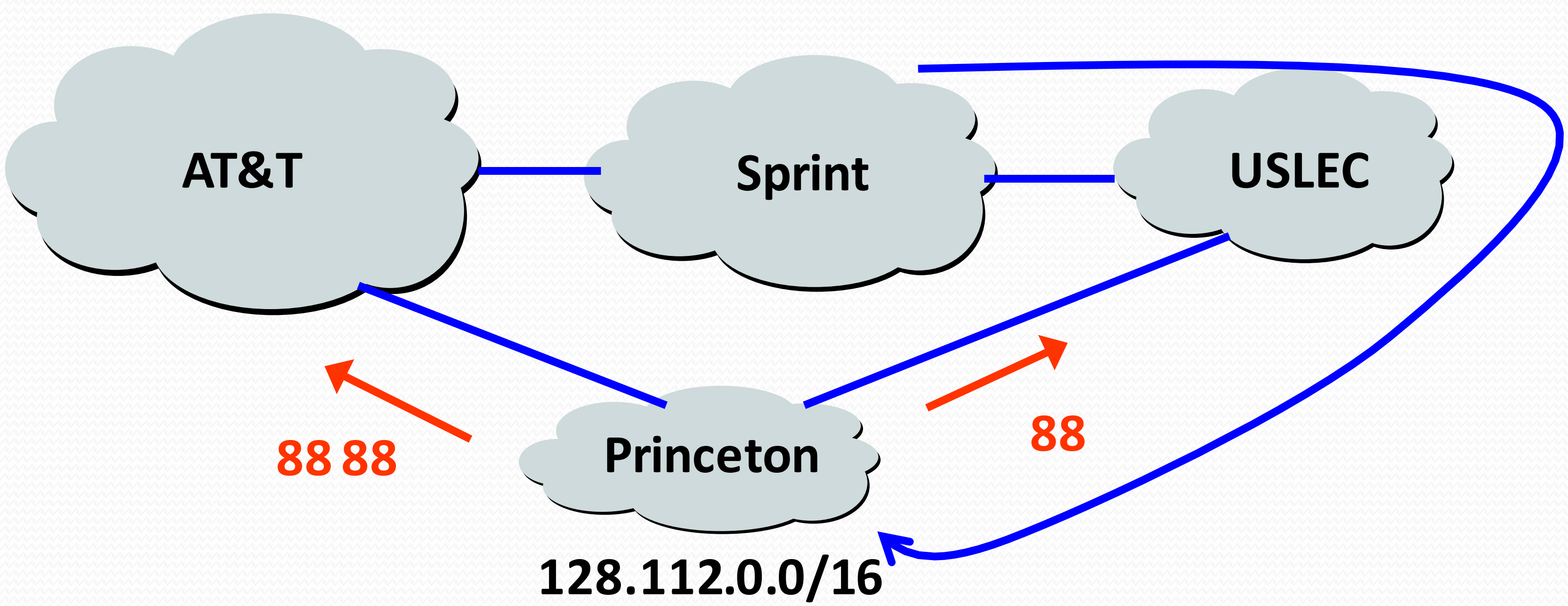
Export Policy: Filtering

- 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

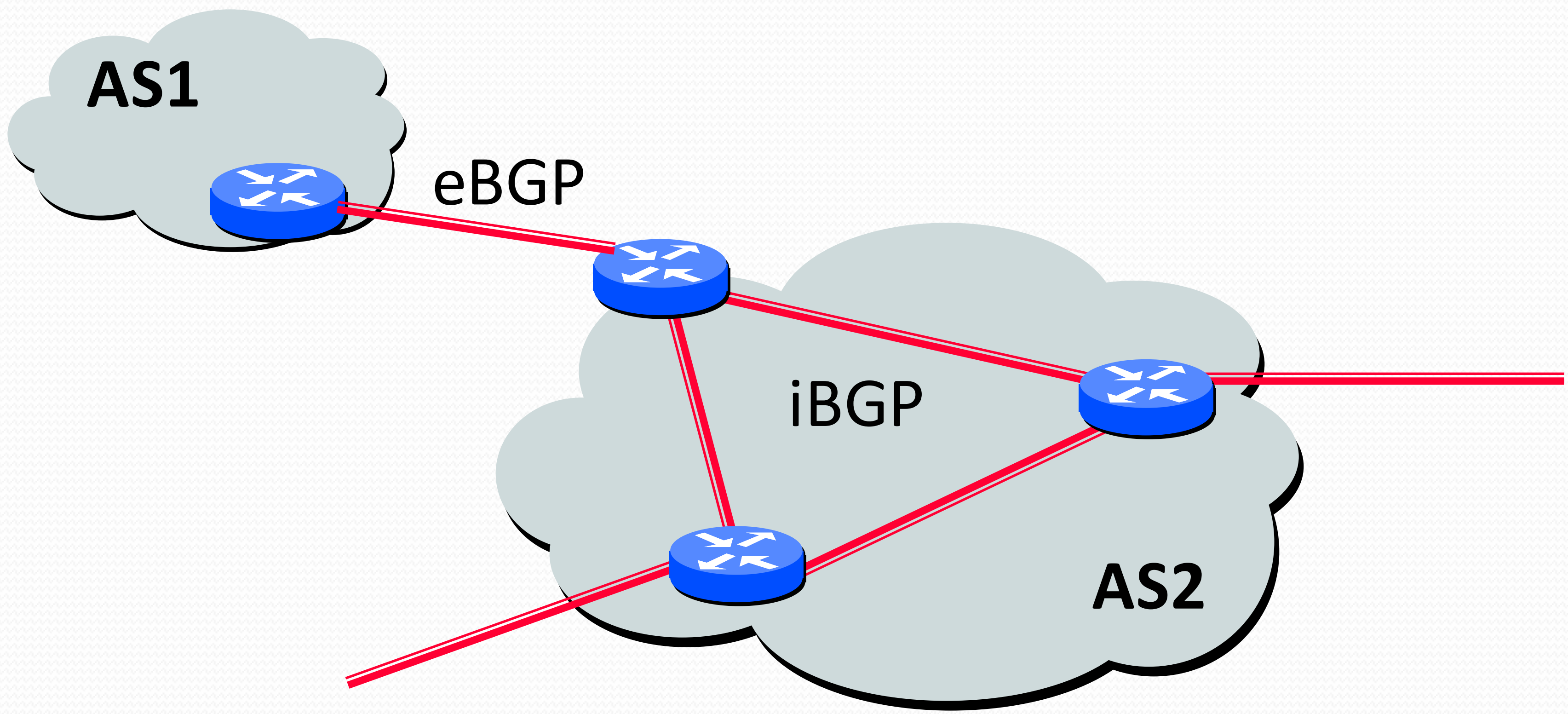


BGP Policy Configuration

- 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

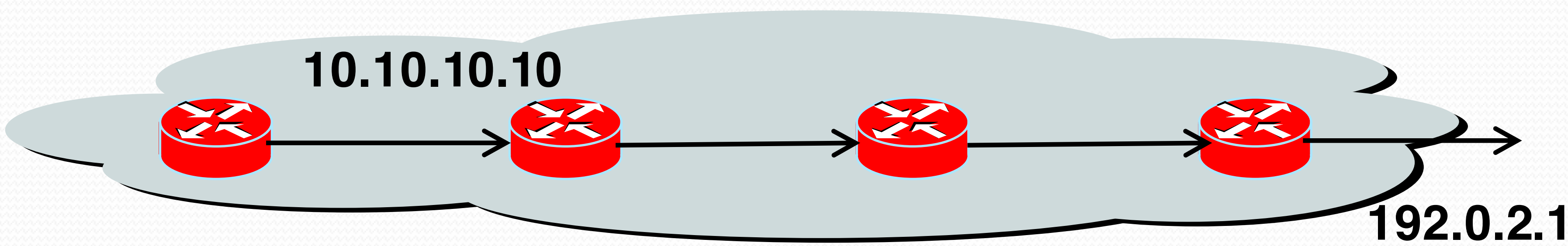
AS is Not a Single Node

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

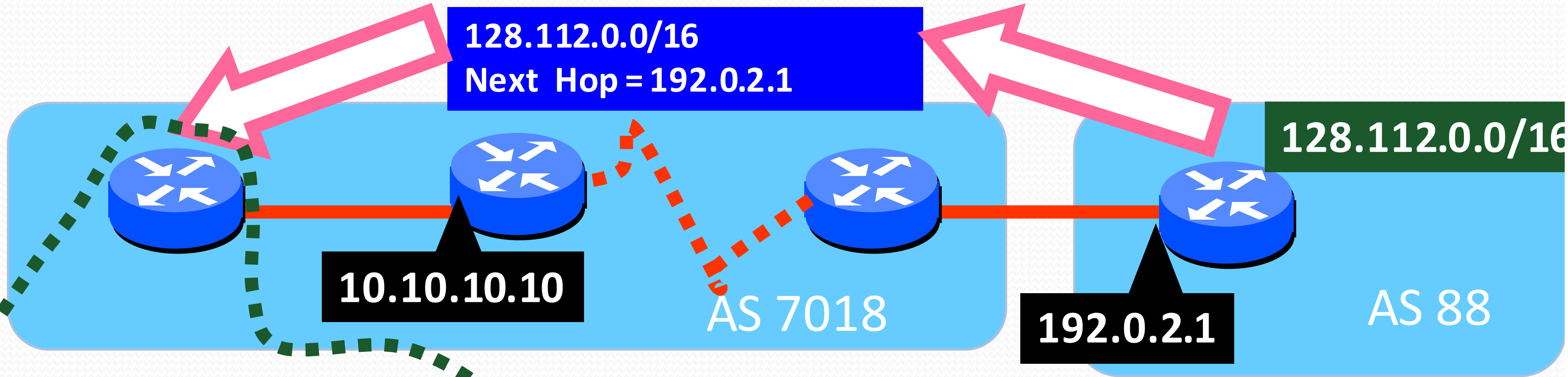


Joining BGP and IGP Information

- 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

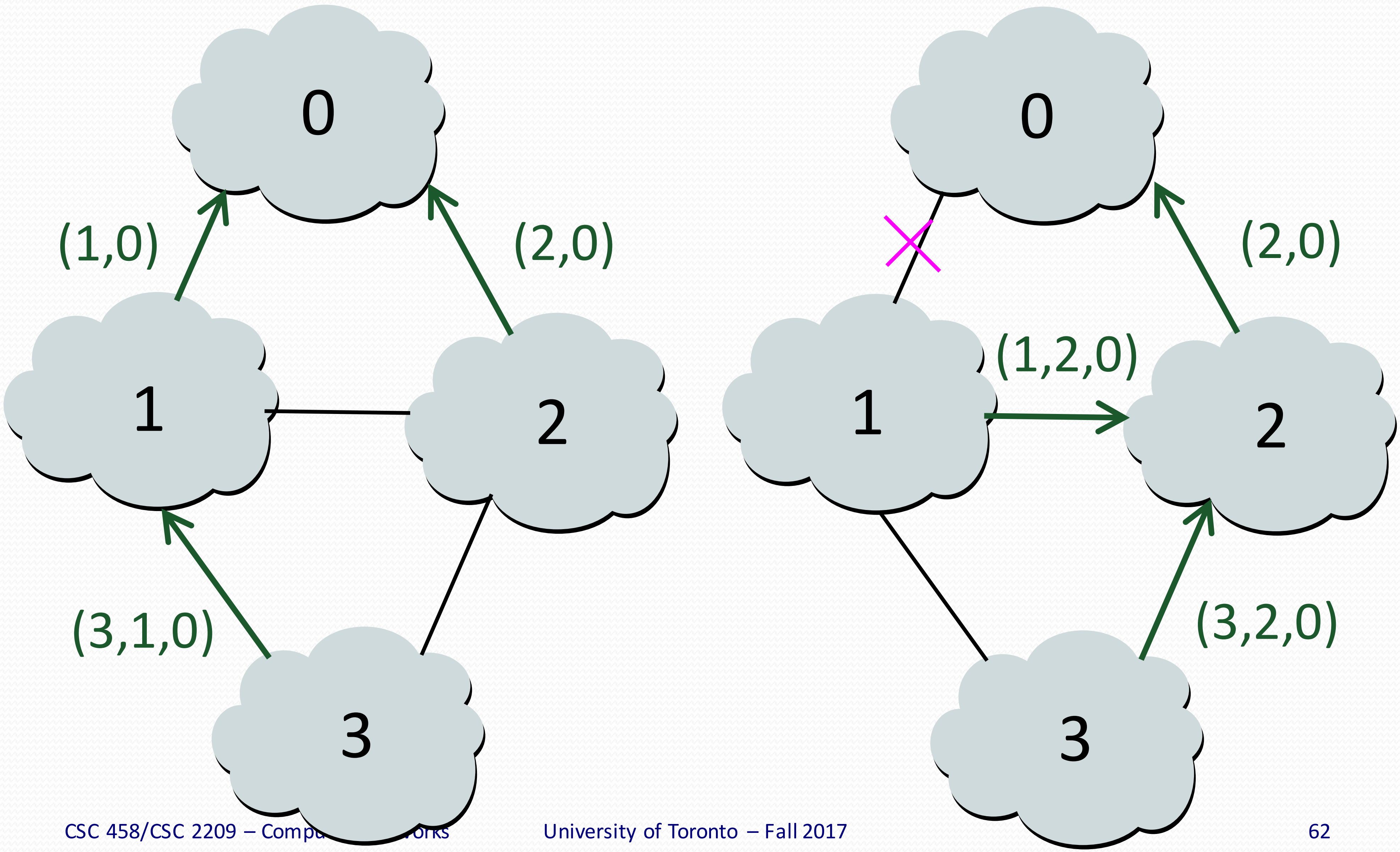
Forwarding Table

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

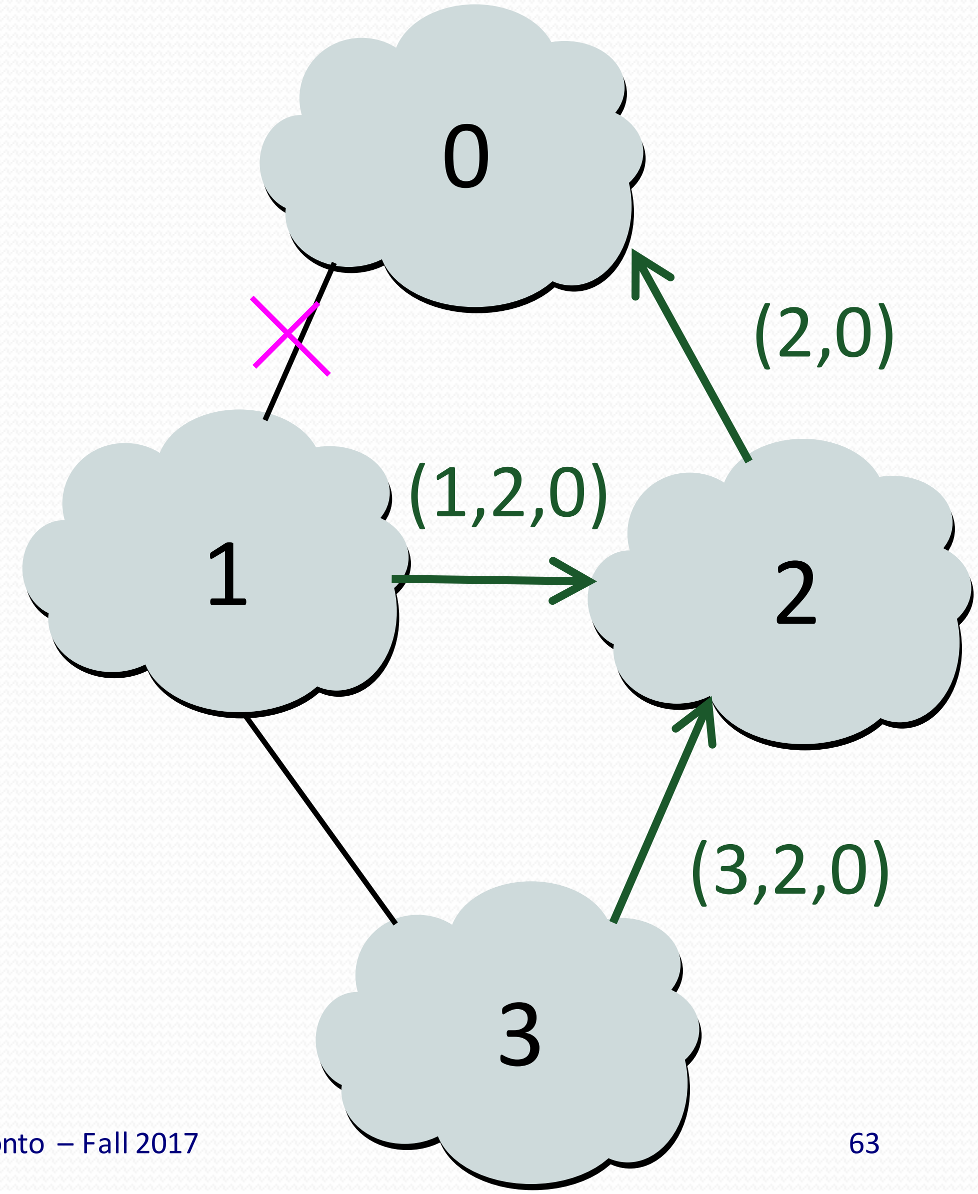
- Topology changes
  - Equipment going up or down
  - Deployment of new routers or sessions
- BGP session failures
  - Due to equipment failures, maintenance, etc.
  - Or, due to congestion on the physical path
- Changes in routing policy
  - Reconfiguration of preferences
  - Reconfiguration of route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

Routing Change: Before and After



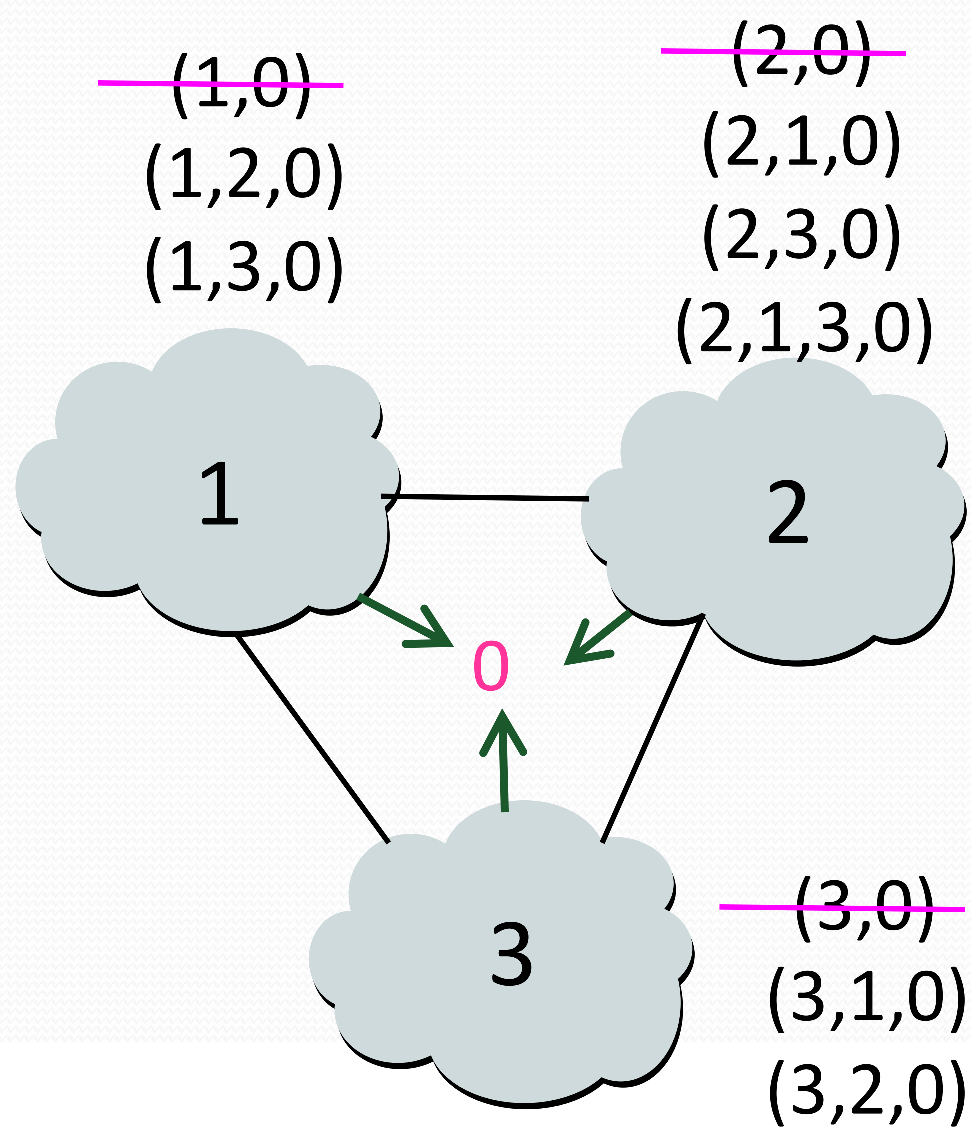
Routing Change: Path Exploration

- 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



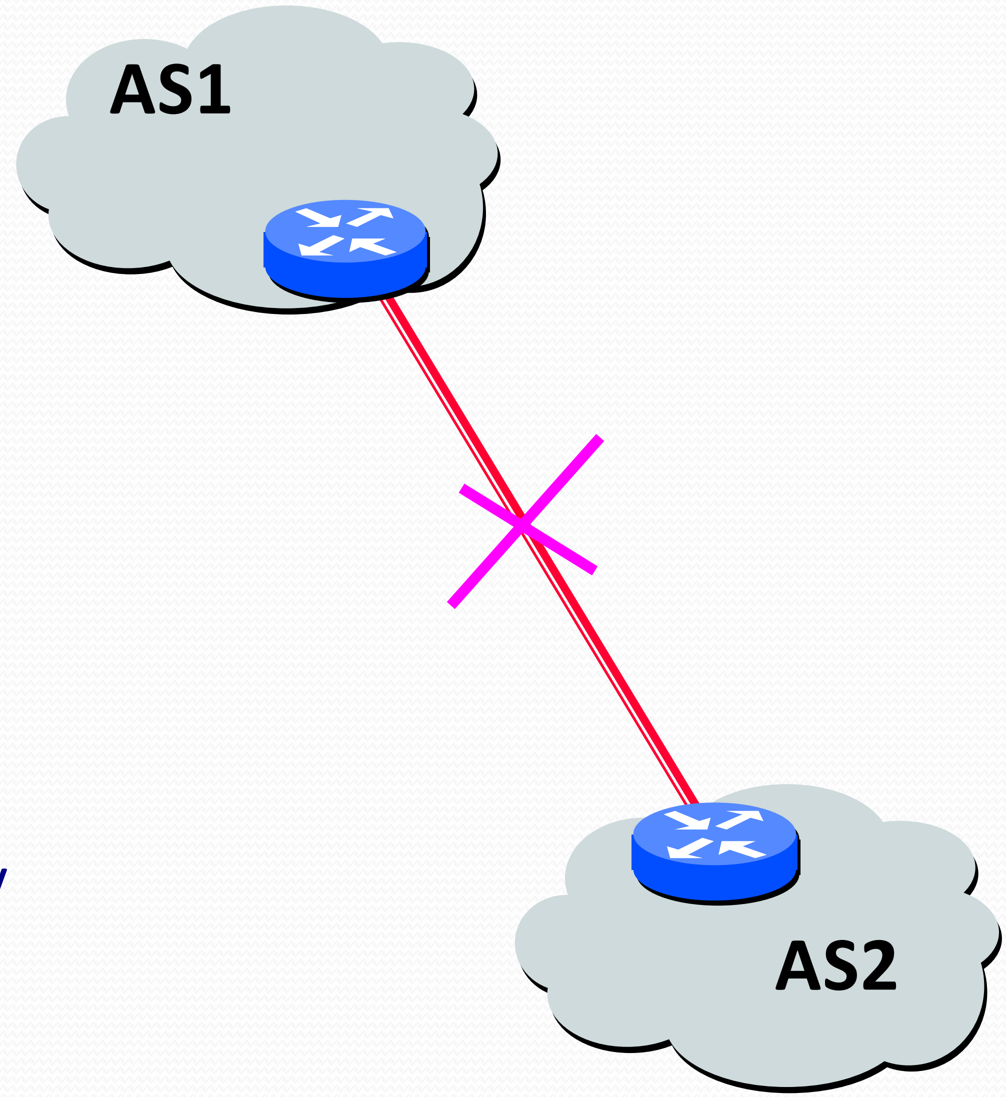
Routing Change: Path Exploration

- 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