15-441/641: Computer Networks
BGP – Inter-domain Routing

15-441 Spring 2019
Profs **Peter Steenkiste** & Justine Sherry

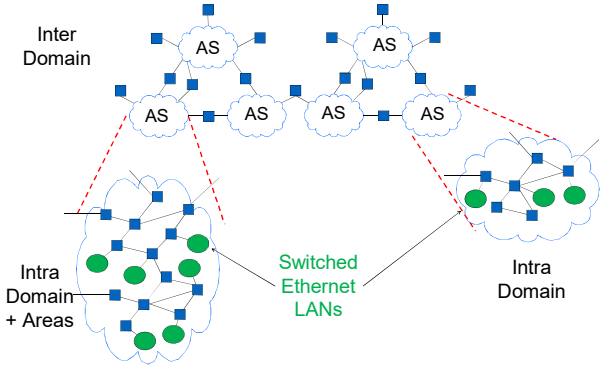
Fall 2019
https://computer-networks.github.io/sp19/

Carnegie Mellon University

Outline

- Routing hierarchy
- Internet structure
- External BGP (E-BGP)
- Internal BGP (I-BGP)

Inter and Intra-Domain Routing



Internet's Area Hierarchy

- What is an Autonomous System (AS)?
  - A set of routers under a single technical administration, using an *interior gateway protocol (IGP)* and common metrics to route packets within the AS and using an *exterior gateway protocol (EGP)* to route packets to other AS's
- Each AS assigned unique ID
  - Only transit domains really need it
- ASes peer with other ASes at network exchanges
  - "Gateway routers" forward packets across ASes

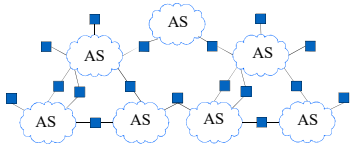
AS Numbers (ASNs)

ASNs are 16 bit values 64512 through 65535 are “private”

- Genuity: 1
- MIT: 3
- CMU: 9
- UC San Diego: 7377
- AT&T: 7018, 6341, 5074, …
- UUNET: 701, 702, 284, 12199, …
- Sprint: 1239, 1240, 6211, 6242, …
- …

ASNs represent units of routing policy

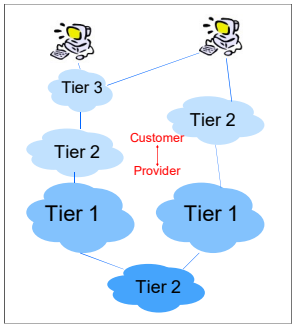
A Logical View of the Internet?



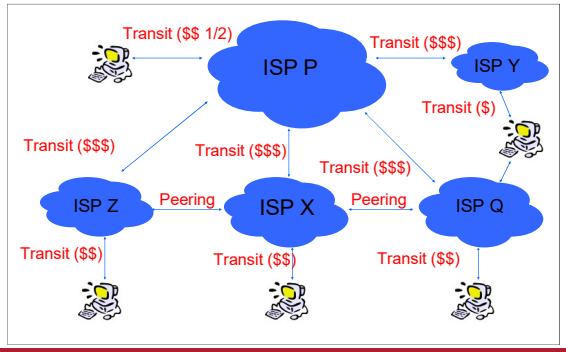
- Logical consequence of hierarchy: repeat the intra-domain solutions at inter-net level
- Based on IP and OSPF style routing protocol
- Not so fast!

A Logical View of the Internet

- ASes are commercial entities
  - Must make money!
- They play different roles in the Internet
  - Tier 1 ISP: global, internet wide connectivity
  - Tier 2 ISP: regional or country-wide
  - Tier 3 ISP: local
- This is an emergent property:
  - Businesses specialize
  - Business relationships



A More Interesting Example



Policy and Economics Rules

- WHY?
  - Consider the economics of the Internet
  - Why does an ISP forward packets?
- Emergent property: “Valley-free” routing
  - Number links as (+1, 0, -1) for provider, peer and customer
  - In any path should only see sequence of +1, followed by at most one 0, followed by sequence of -1
  - -1 → 0 → +1corresponds to a valley and means an ISP is forwarding packets for free
    - Worse: it is paying its providers for forwarding

Outline

- Routing hierarchy
- Internet structure
- External BGP (E-BGP)
- Internal BGP (I-BGP)

History

- Mid-80s: EGP
  - Reachability protocol (no shortest path)
  - Did not accommodate cycles (assumes tree topology)
  - Evolved when all networks connected to NSF backbone
- Commercialization led to richer topologies – Result: BGP introduced as routing protocol
  - Latest version is BGP-4 - supports CIDR
  - Primary objective:
    - Connectivity not performance
    - Respect business relationships
    - Allow for local policies in each AS

Choices

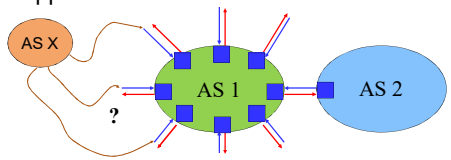
- Link state or distance vector?
  - Constraint: No universal metric – local policy decisions
- Problems with link state:
  - If routers do not use the same metric – loops
  - Link state database too large – entire Internet
  - May expose policies to other AS’s
- Problems with distance-vector:
  - Bellman-Ford algorithm may converge slowly
  - Problems with “count to infinity”

Solution: Distance Vector with Path

- Each routing update carries the entire path
- Loops are detected as follows:
  - When AS gets route, check if its AS number is already in the path
    - If yes, reject route
    - If no, add self and (possibly) advertise route further
- Advantage:
  - Metrics are local - AS chooses path, protocol ensures no loops

Policy-based Routing: AS 1 to X

1. Receive reachability destination for destination X
   - AS1 selects its path to X based on local policies
2. AS1 advertise its path to X selectively
   - Use local policies to decide who to advertise it to
- Colors are flipped for AS 2



Interconnecting BGP Peers

- BGP uses TCP to connect peers
- Advantages:
  - Simplifies BGP
  - No need for periodic refresh - routes are valid until withdrawn, or the connection is lost
  - Incremental updates
- Disadvantages
  - Congestion control on a routing protocol?
  - Poor interaction with other traffic during high load

Hop-by-hop Model

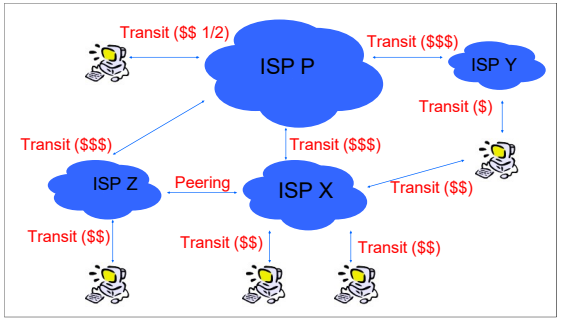
- BGP only advertises routes that it uses to its neighbors
- Consistent with the hop-by-hop Internet paradigm
  - e.g., AS1 cannot forward AS2's packets to other AS's in a manner different than what AS2 has chosen
  - Worse: can lead to forwarding loops
- BGP enforces policies by

1. choosing paths from multiple alternatives and
2. controlling advertisement to other AS's

Examples of BGP Policies

- A multi-homed stub AS refuses to act as transit
  - Limit path advertisement
- A multi-homed AS can become transit for some AS's
  - Only advertise paths to some AS's
- An AS can favor or disfavor certain AS's for traffic transit from itself
  - By choosing those paths among the options

Some Examples



BGP Messages

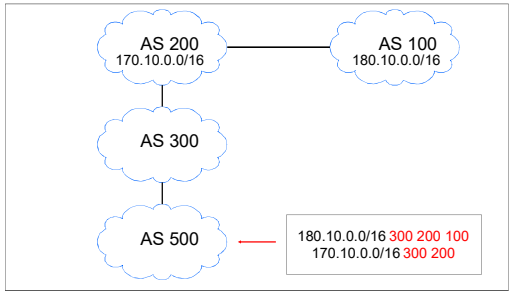
- Open
  - Announces AS ID
  - Determines hold timer – interval between keep_alive or update messages, zero interval implies no keep_alive
- Keep_alive
  - Sent periodically (but before hold timer expires) to peers to ensure connectivity.
  - Sent in place of an UPDATE message
- Notification
  - Used for error notification
  - TCP connection is closed *immediately* after notification

BGP UPDATE Message

- List of withdrawn routes
- Network layer reachability information
  - List of reachable prefixes
- Path attributes
  - Origin
  - Path
  - Metrics: used by policies for path selection
- All prefixes advertised in message have the same path attributes

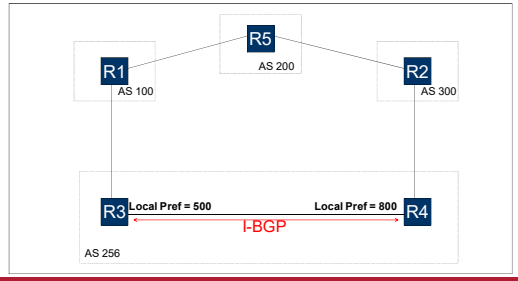
AS_PATH

- List of traversed AS's



LOCAL PREF

- Local (within an AS) mechanism to provide relative priority among BGP routers (e.g. R3 over R4)



LOCAL PREF – Common Uses

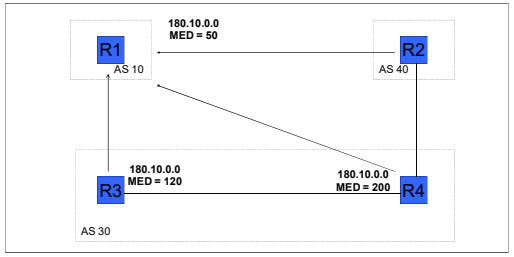
- Routers have a default LOCAL PREF
  - Can be changed for specific ASes
- Peering vs. transit
  - Prefer to use peering connection, why?
- In general, customer > peer > provider
  - Use LOCAL PREF to ensure this

Multi-Exit Discriminator (MED)

- Hint to external neighbors about the preferred path into an AS
  - Non-transitive attribute
    - Different AS choose different scales
- Used when two AS's connect to each other in more than one place

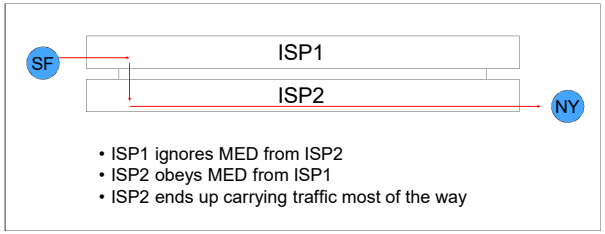
MED

- Hint to R1 to use R3 over R4 link
- Cannot compare AS40's values to AS30's



MED

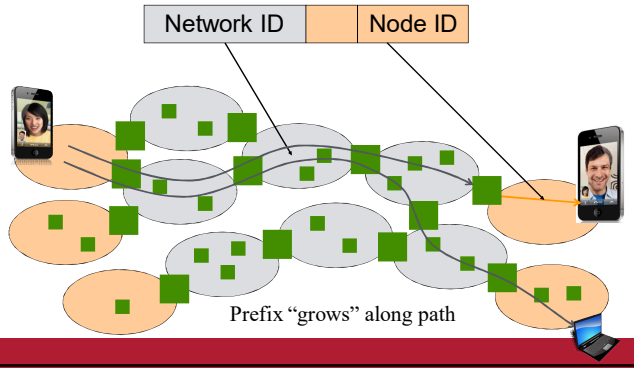
- MED is typically used in provider/subscriber scenarios
- It can lead to unfairness if used between ISP because it may force one ISP to carry more traffic:



Path Selection Criteria

- Attributes + external (policy) information
- Rough ordering for path selection
  - Highest LOCAL-PREF
    - Captures business relationships and other factors
  - Shortest AS-PATH
  - Lowest origin type
  - Lowest MED (if routes learned from same neighbor)
  - eBGP over iBGP-learned
  - Lowest internal routing cost to border router
  - Tie breaker, e.g., lowest router ID

Routing and Forwarding in the Internet: Prefixes

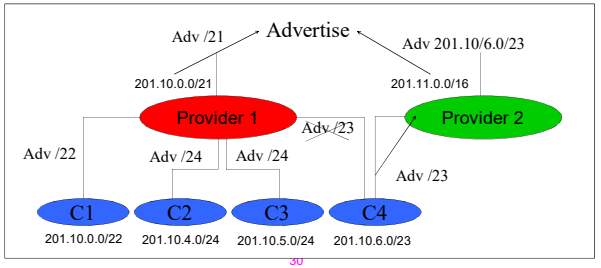


BGP and Prefixes

- BGP advertisements specify prefix reachability
  - Prefix ≈ network ID in a CIDR world
- BGP can also merge advertisements:
  - Example: 4 “/20” advertisements that share the top 18 bits in their prefix can become a single “/18” adv., if the reachability information is the same
- Can also leverage the longest prefix rule to merge entries:
  - Example: if only three of the prefix share reachability information, you can create a “/18” and a “/20” prefix

Example

- Client advertise their prefixes
- Provider one can merge advertisements
- If C4 uses Provider 2, it will be longer prefix

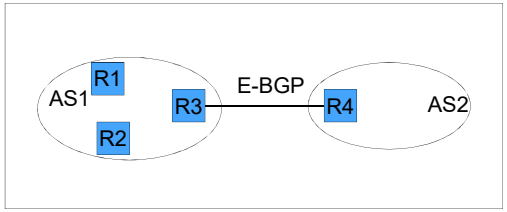


Outline

- Routing hierarchy
- Internet structure
- External BGP (E-BGP)
- Internal BGP (I-BGP)

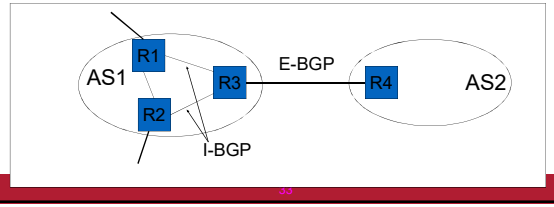
Internal vs. External BGP

- BGP can be used by R3 and R4 to learn routes
- How do R1 and R2 learn routes?
- Border gateways also need to run an internal routing protocol
  - Establish connectivity between routers inside AS
- I-BGP: uses same messages as E-BGP

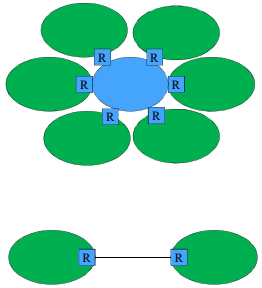


I-BGP Route Advertisements

- I-BGP uses different rules about re-advertising prefixes:
  - Prefix learned from E-BGP can be advertised to I-BGP neighbor and vice-versa, but
  - Prefix learned from I-BGP neighbors cannot be advertised to other I-BGP neighbors → direct connections (TCP) for I-BGP routers
  - Reason: AS PATH is the same AS and thus danger of looping.



How Do ISPs Peer?



- Public peering: use network to connect large number of ISPs in Internet eXchange Point (IXP)
  - Managed by IXP operator
  - Layer 2 private network
  - Efficient: can have 100s of ISPs
  - Has led to increase in peering
- Private peering: directly connect ISP border routers
  - Set up as private connection
  - Typically done in an Internet eXchange Point (IXP)

Important Concepts

- Wide area Internet structure and routing driven by economic considerations
  - Customer, providers and peers
- BGP designed to:
  - Provide hierarchy that allows scalability
  - Allow enforcement of policies related to structure
- Mechanisms
  - Path vector – scalable, hides structure from neighbors, detects loops quickly