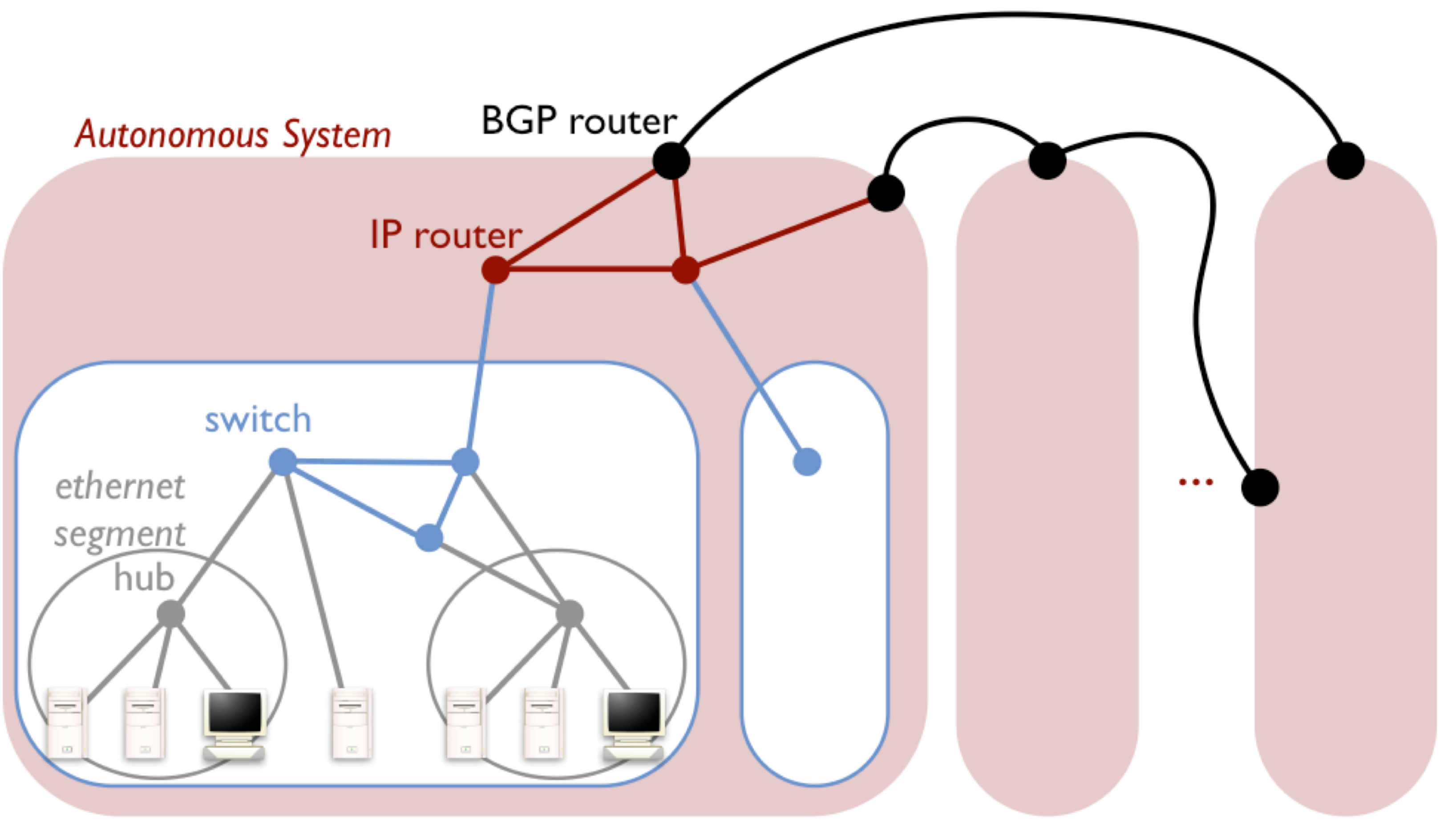
The Global Internet

Big Picture of the Internet



The Global Internet and Inter-domain Routing

- Why does Border Gateway Protocol (BGP) exist?
  - What is interdomain routing and why do we need it?
  - Why does BGP look the way it does?
- How does BGP work?
  - Path vector algorithm
  - Various boring details
- pay more attention to the "why" than the "how"

Routing

- Provides paths between networks
- We know several designs already
  - link-state
  - distance vector
- But previous lectures assumed single "domain"
  - all routers have same routing metric (shortest path)
  - no privacy issues, no policy issues

Internet is more complicated.....

- Internet not just unstructured collection of networks
- Internet is comprised of a set of "autonomous systems" (ASes)
  - Independently run networks, some are commercial ISPs
  - Autonomy of control: ex: company, university, etc
  - Currently around 35,000 Ases
- Enables hierarchical aggregation of routing information
- ASes are sometimes called "domains"
  - hence "interdomain routing"

Autonomous Systems

- Intradomain Routing (within an AS)
  - Performed using domain-specific algorithm
  - Selected by domain administrators
  - Allows heterogeneous interior gateway protocols (IGP)
- Interdomain Routing (between AS’s)
  - Performed using standard global algorithm
  - Homogeneous exterior gateway protocol (EGP)
  - Main goal: reachability

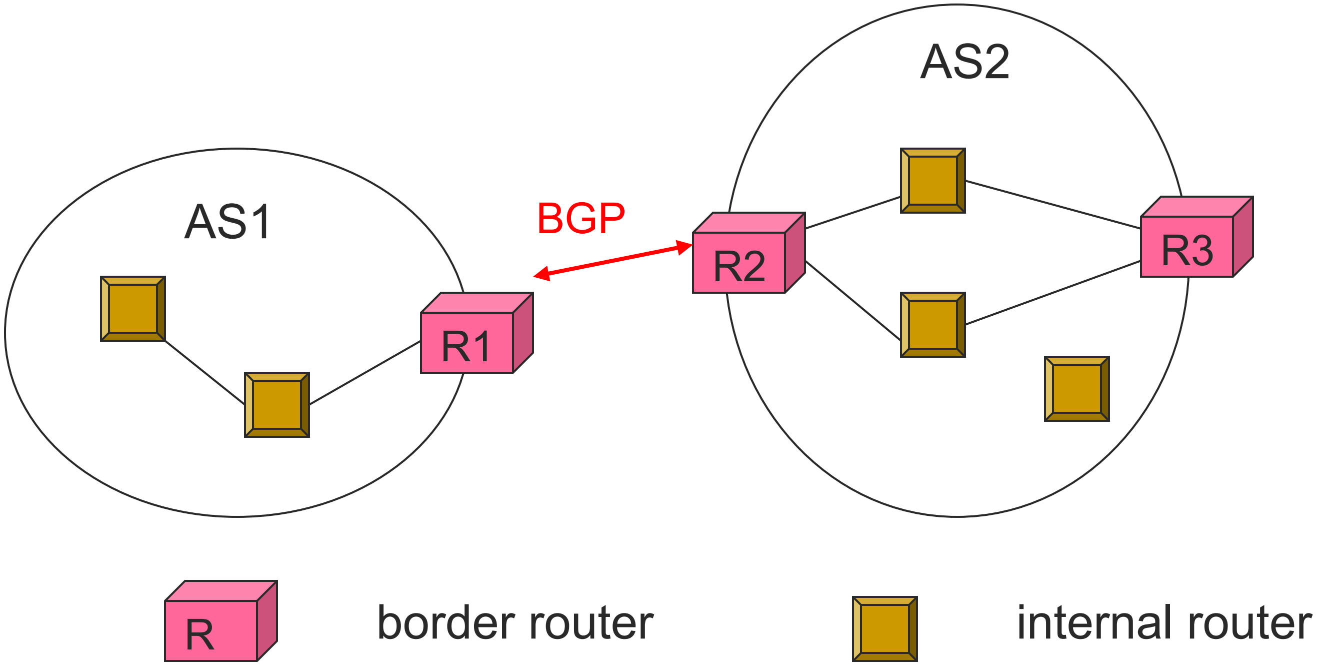
Autonomous Systems

- Common intradomain routing protocols
  - Routing Information Protocol (RIP)
    - From the early Internet
    - Part of Berkeley Software Distribution (BSD) Unix
    - Distance vector algorithm
    - Based on hop count (infinity set to 16 hops)
  - Open Shortest Path First (OSPF)
    - Internet Standard (RFC 2328)
    - Link state algorithm
    - Authenticates messages
    - Load balances across links

Autonomous Systems

- Standard interdomain routing protocols
  - General aspects
    - Very complex and difficult
    - Focuses on reachability rather than optimality
    - Must be loop free
    - Specify how reachability information should be exchanged
  - Exterior Gateway Protocol (EGP)
    - Defined on Internet with tree structure
    - Embodied (and enforced) tree structure
    - Had to be replaced eventually
    - Distance vector updates
  - Border Gateway Protocol (BGP)
    - Replaced EGP

BGP



- Border routers
  - Connects an AS to the Internet
  - Used for default external route

Autonomous Systems

Share connectivity information across ASes

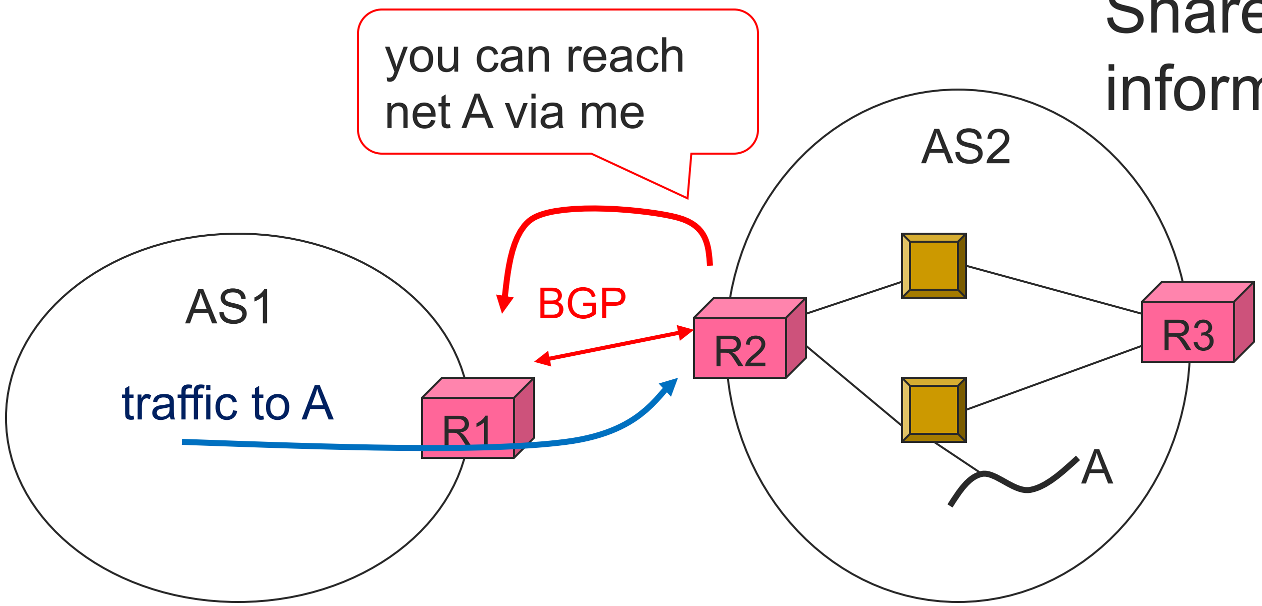
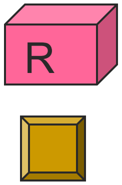


table at R1:

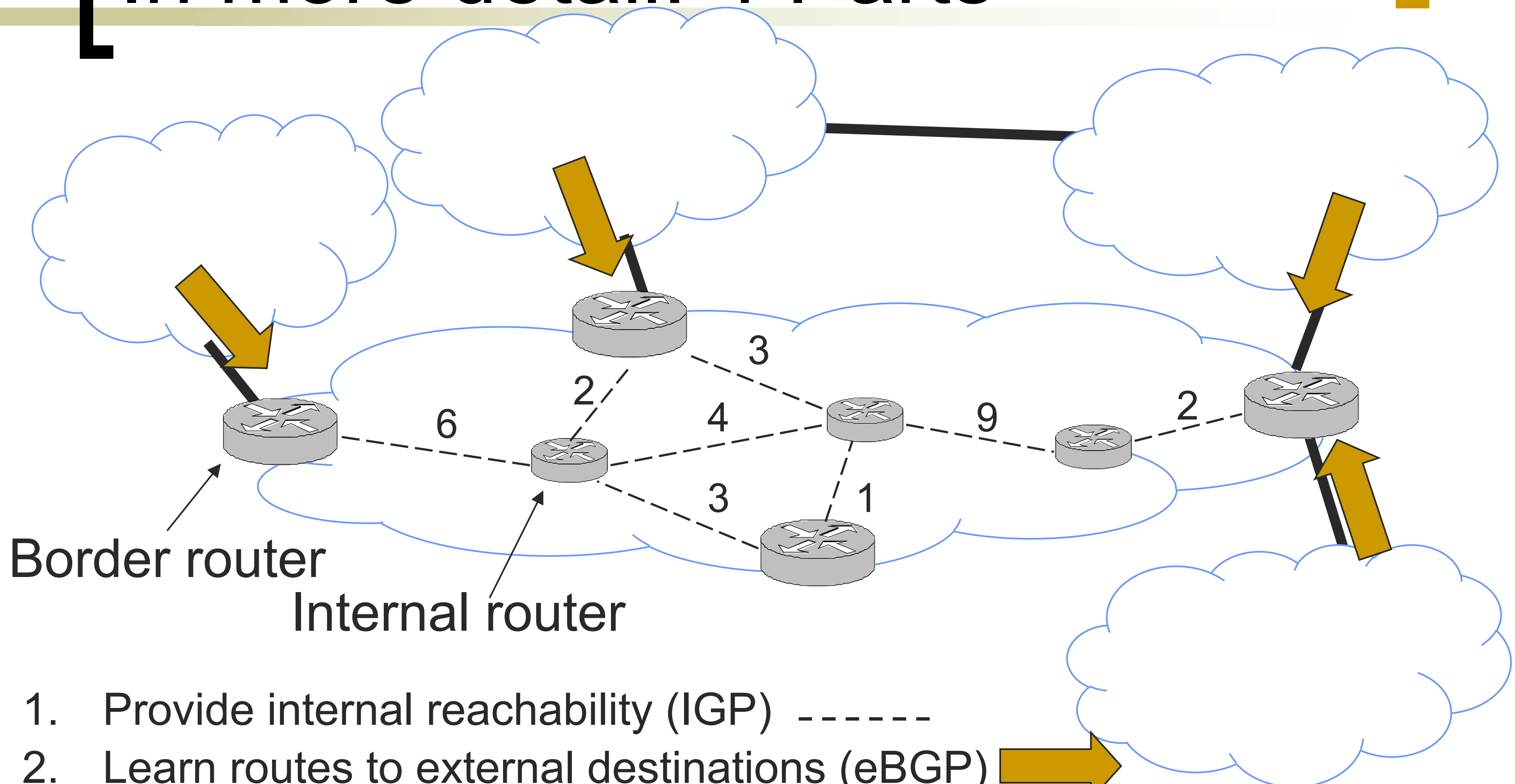
dest	next hop
A	R2



border router

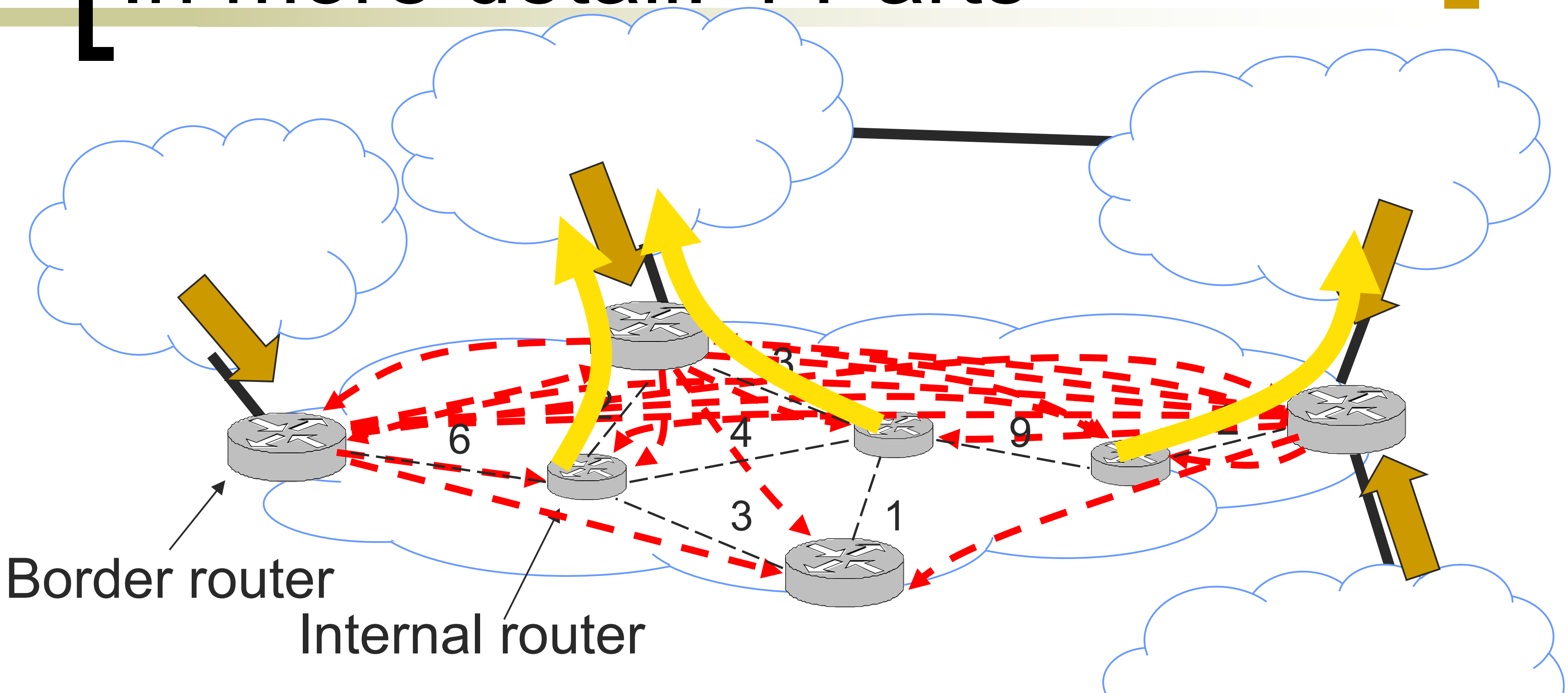
internal router

In more detail: 4 Parts



1. Provide internal reachability (IGP) - - - - - -
2. Learn routes to external destinations (eBGP)

In more detail: 4 Parts



3. Distribute externally learned routes internally (iBGP)
4. Select closest egress (IGP) ------

The ‘A’ in AS really means Autonomous

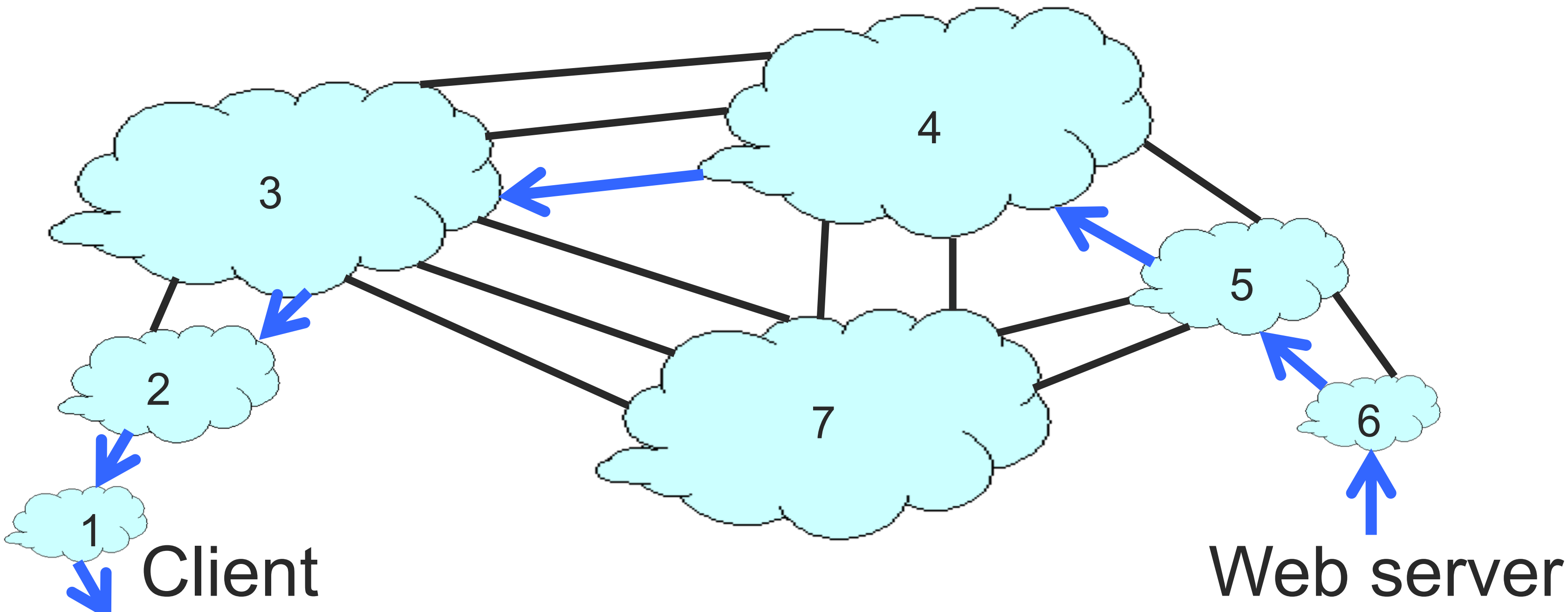
- Want to choose their own internal routing protocol
  - Different algorithms and metrics
- Want freedom to route based on policy
  - “My traffic can’t be carried over my competitor’s network”
  - “I don’t want to carry transit traffic through my network”
  - Not expressible as Internet-wide “shortest path”!
- Want to keep their connections and policies private
  - Would reveal business relationships, network structure

AS’ s are Buisinesses

- Three kinds of common relationships between ASes
  - AS A can be AS B’ s *customer*
  - AS A can be AS B’ s *provider*
  - AS A can be AS B’ s *peer*
- Business implications
  - Customer pays provider, peers don’ t pay each other
- Policy implications
  - “When sending traffic, I prefer to route through customers over peers, and peers over providers”
  - “I don’ t carry traffic from one provider to another provider”

AS-Level Topology

- Destinations are IP prefixes (e.g., 12.0.0.0/8)
- Nodes are Autonomous Systems (ASes)
- Links are connections & business relationships



Autonomous Systems

- Challenges
  - Scale
    - Border router must be able to forward any packet destined anywhere in the Internet
  - Autonomous routing in AS’s
    - Impossible to calculate meaningful costs for paths that cross multiple AS’s
  - Trust
    - One AS must trust the advertised routes of other AS’s
- Goal
  - Specify polices that lead to “good” paths (even if they are not optimal)

Routing Choices

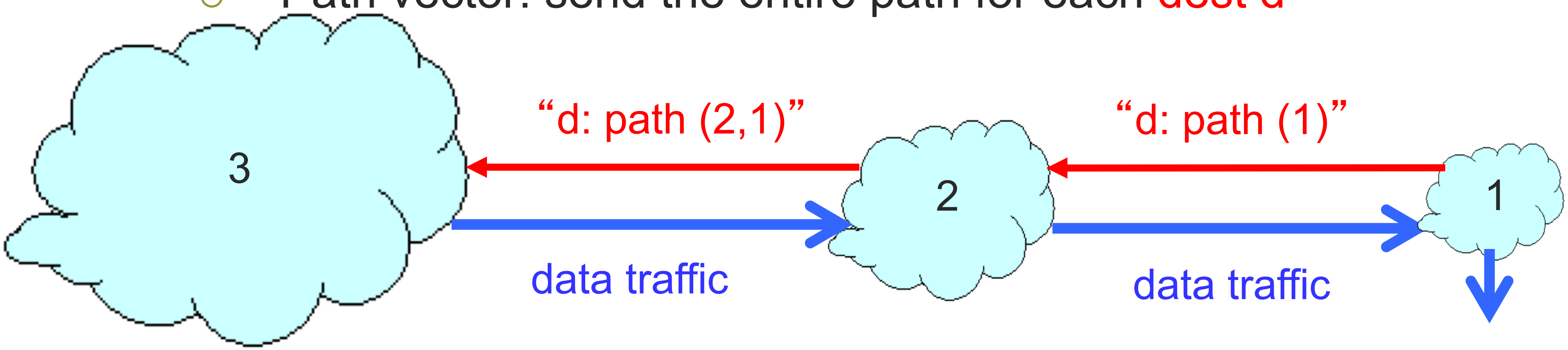
- Key issues are *policy* and *privacy*
- Challenges
  - No universal metric
  - AS-specific Policy decisions
- Problems with link state
  - Metric used by routers not the same
    - Can’t use shortest path - loops
  - LS database too large - entire Internet
  - Flooding may expose internal topology and policies to other AS’s

Routing Choices

- Key issues are *policy* and *privacy*
- Challenges
  - No universal metric
  - AS-specific Policy decisions
- Problems with distance-vector
  - Does not reveal any connectivity information
  - But still uses shortest path
  - Slow to converge

Solution: Path Vector Routing

- Extension of distance-vector routing
  - Support flexible routing policies
  - Faster loop detection (no count-to-infinity)
- Key idea: advertise the entire path
  - Distance vector: send distance metric per dest d
  - Path vector: send the entire path for each dest d

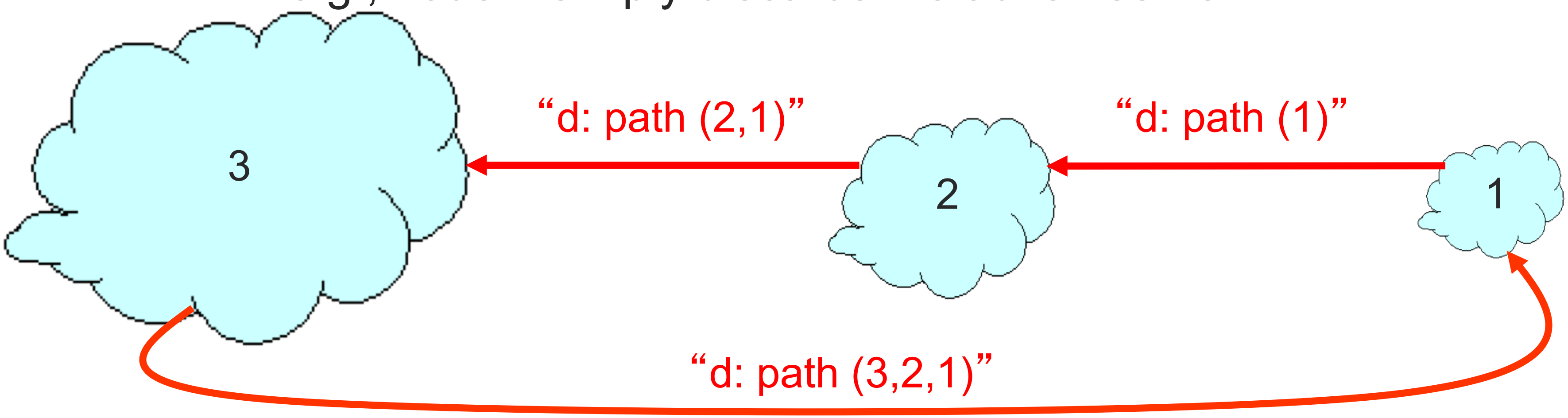


Path Vectors

- Each routing update carries the entire path
- Loops are detected as follows
  - When AS gets route check if AS already in 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

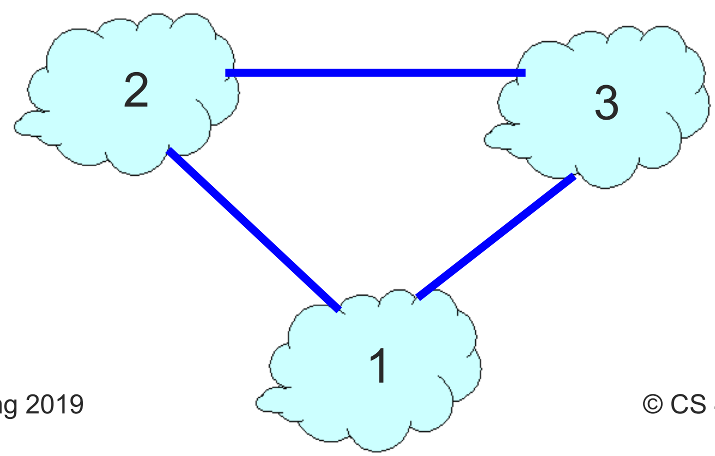
Loop Detection

- 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

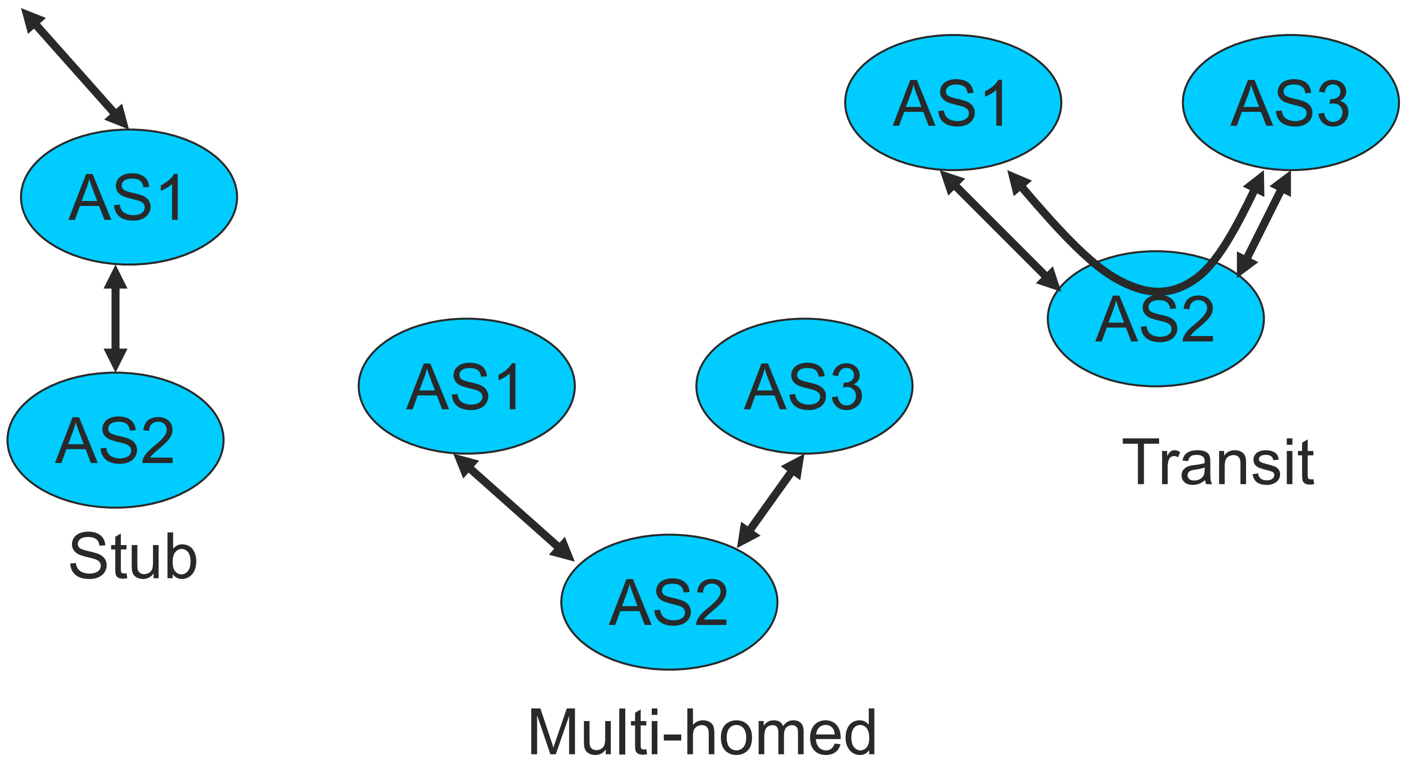
- Each node can apply local policies
  - Path selection: Which path to use?
  - Path export: Which paths to advertise?
- Examples
  - Node 2 may prefer the path "2, 3, 1" over "2, 1"
  - Node 1 may not let node 3 hear the path "1, 2"



AS Categories

- Stub
  - An AS that has only a single connection to one other AS - carries only local traffic
- Multi-homed
  - An AS that has connections to more than one AS, but does not carry transit traffic
- Transit
  - An AS that has connections to more than one AS, and carries both transit and local traffic (under certain policy restrictions)

AS Categories

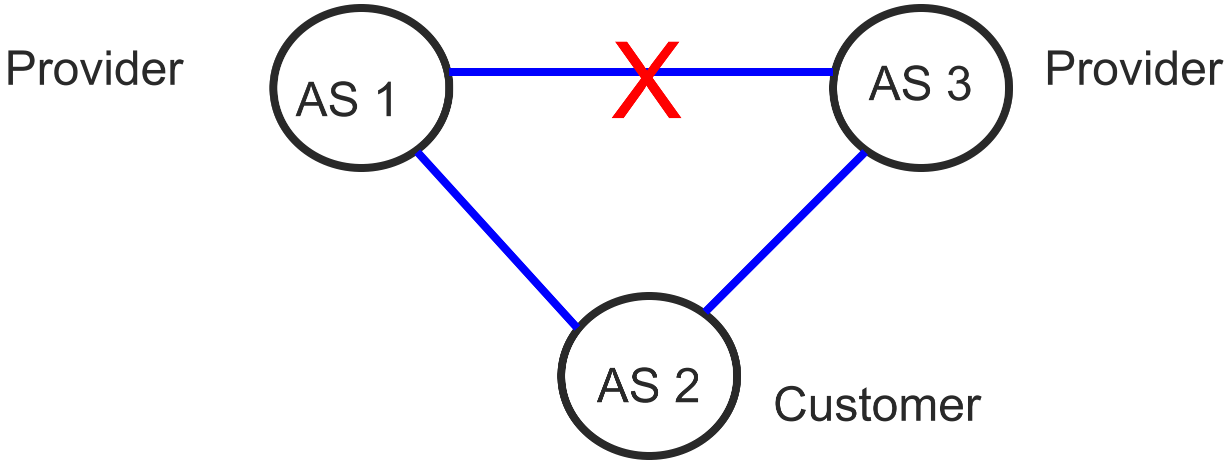


Issues with Path-Vector Policy Routing

- Reachability
- Security
- Performance
- Lack of isolation
- Policy oscillations

Reachability

- Normal routing
  - If graph is connected, reachability is assured
- Policy routing
  - Does not always hold



Security

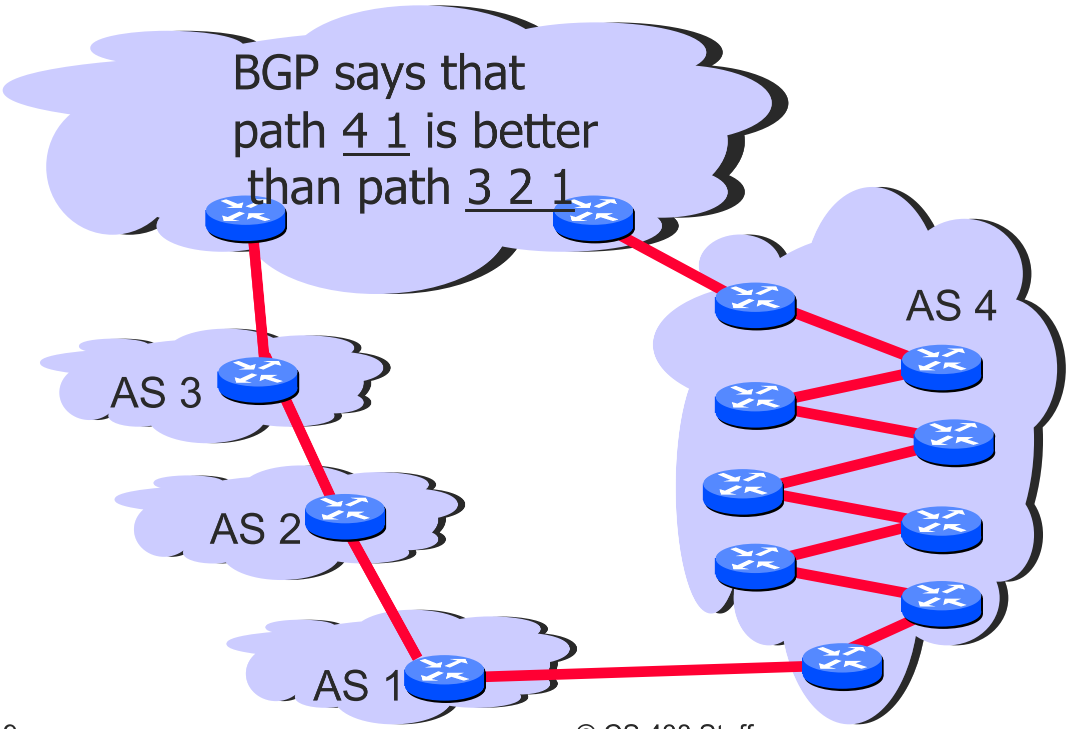
- An AS can claim to serve a prefix that they actually don’t have a route to (blackholing traffic)
  - Problem not specific to policy or path vector
  - Important because of AS autonomy
- Even worse: snoop on all traffic to almost any destination
  - Without anyone realizing that anything is wrong
- Fixable: make ASes “prove” they have a path
  - But not used in today’s Internet

Performance

- BGP designed for policy not performance
- “Hot Potato” routing common but suboptimal
  - AS wants to hand off the packet as soon as possible
- Even BGP “shortest paths” are not shortest
  - Fewest AS’s != Fewest number of routers
- 20% of paths inflated by at least 5 router hops
- Not clear this is a significant problem

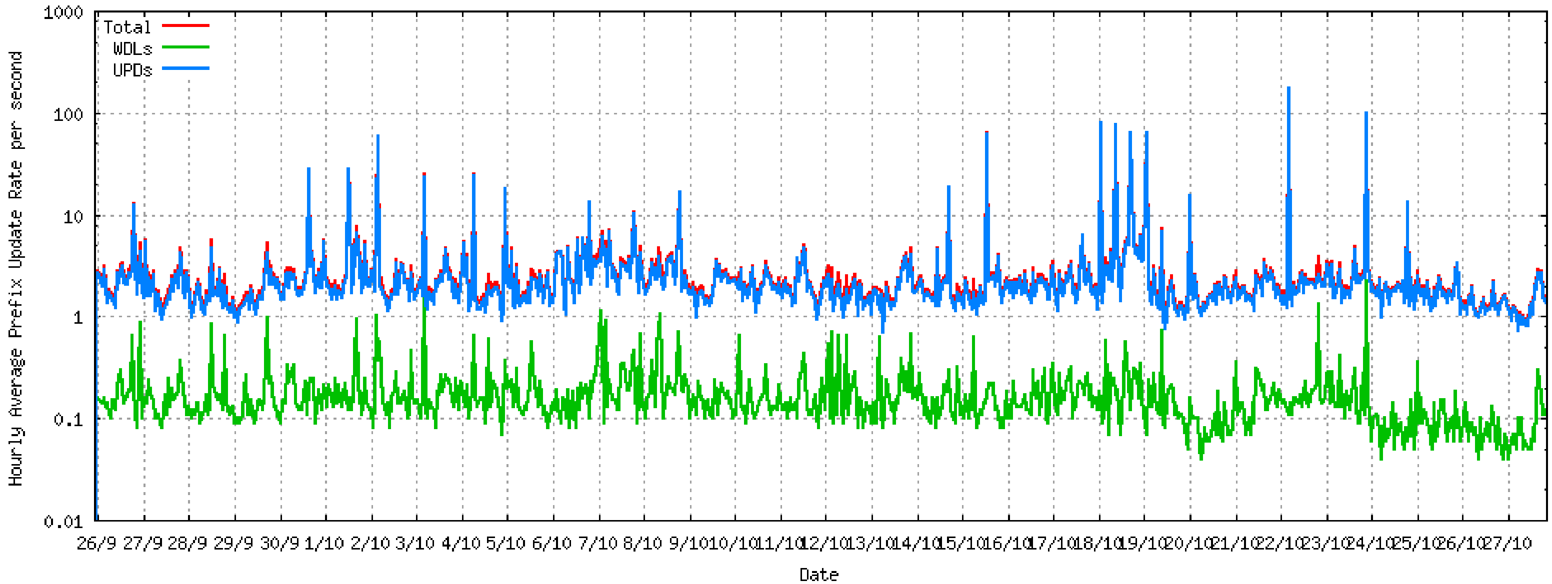
Performance

- AS path length can be misleading
  - An AS may have many router-level hops



Lack of Isolation: Dynamics

- Change in the path
  - Path must be re-advertised to every node using the path
  - "Route Flap Damping" supposed to help (but ends up causing more problems)

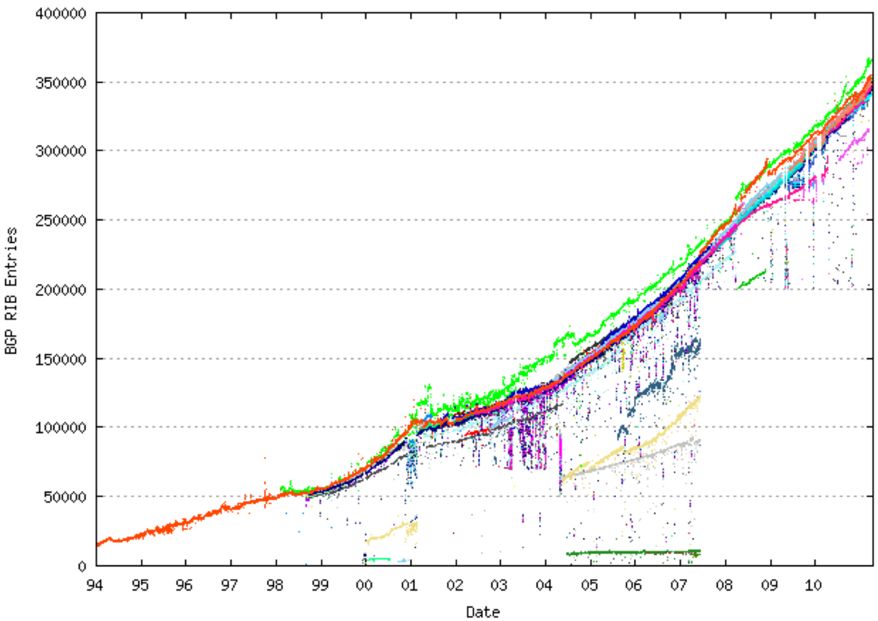


BGP updates per hour per prefix

Lack of isolation: Routing Table Size

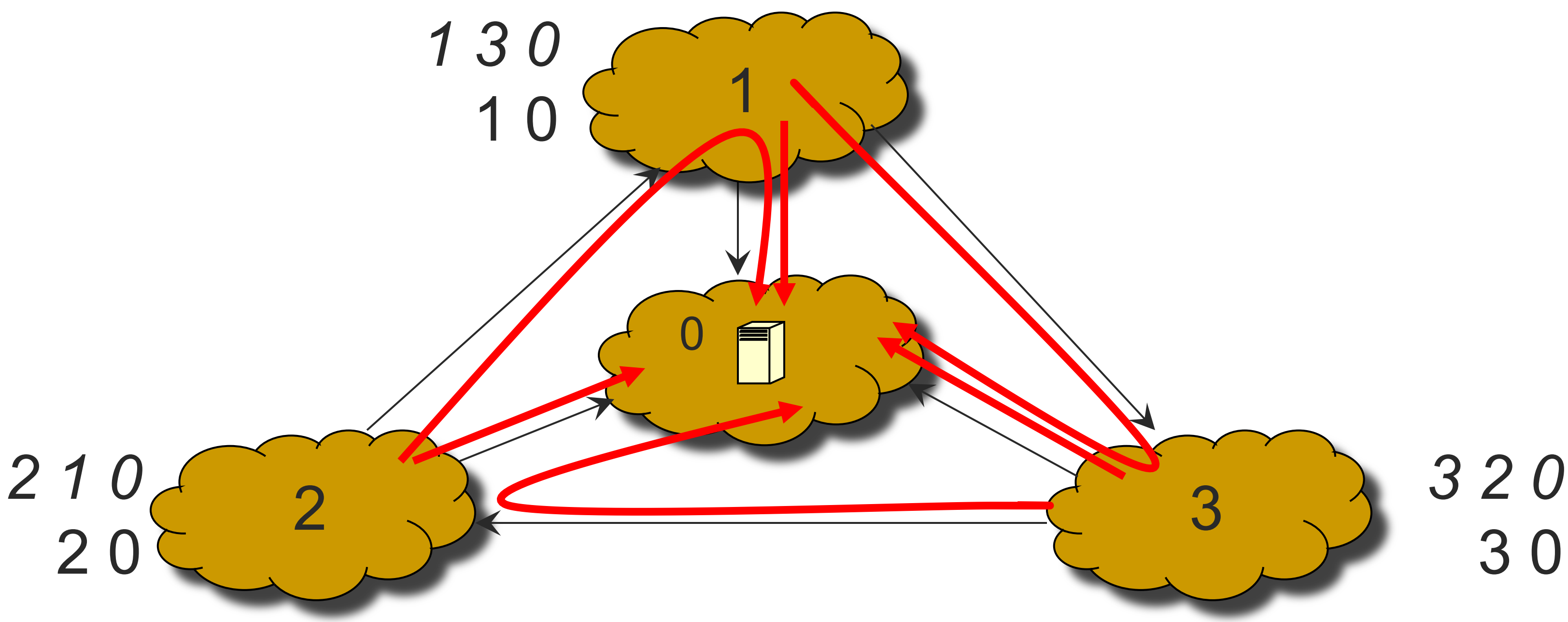
- Each BGP router must know path to every other IP prefix
  - But router memory is expensive and thus constrained
- Number of prefixes growing more than linearly
- Subject of current research

Number of prefixes in BGP table



Persistent Oscillations due to Policies

Depends on the interactions of policies



We are back to where we started!

Policy Oscillations

- Policy autonomy vs network stability
  - Focus of much recent research
- Not an easy problem
  - Difficult to decide whether given policies will eventually converge!
- However, if policies follow normal business practices, stability is guaranteed

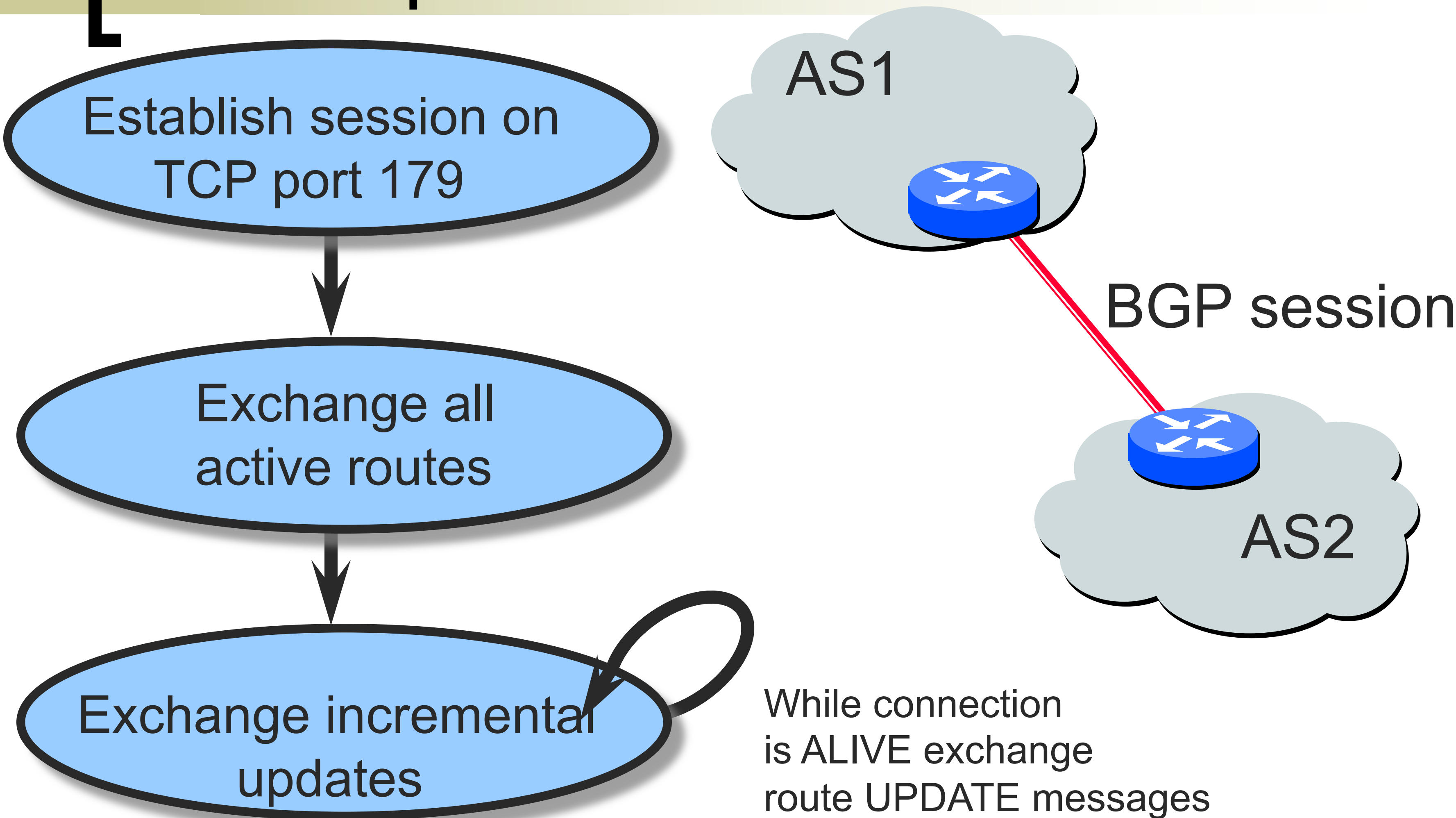
Border Gateway Protocol (BGP)

- Interdomain routing protocol for the Internet
  - Prefix-based path-vector protocol
  - Policy-based routing based on AS Paths
  - Evolved during the past 15 years
- 1989 : BGP-1 [RFC 1105]
  - Replacement for EGP (1984, RFC 904)
- 1990 : BGP-2 [RFC 1163]
- 1991 : BGP-3 [RFC 1267]
- 1995 : BGP-4 [RFC 1771]
  - Support for Classless Interdomain Routing (CIDR)

BGP’s job: maintain routing table

```
ner-routes>show ip bgp
BGP table version is 6128791, local router ID is 4.2.34.165
Status codes: s suppressed, d damped, h history, * valid, > best, i - internal
Origin codes: i - IGP, e - EGP, ? - incomplete
   Network          Next Hop            Metric LocPrf Weight Path
* i3.0.0.0          4.0.6.142             1000     50      0 701 80 i
* i4.0.0.0          4.24.1.35                0    100      0 i
* i12.3.21.0/23     192.205.32.153           0     50      0 7018 4264 6468 ?
* e128.32.0.0/16    192.205.32.153           0     50      0 7018 4264 6468 25 e
```

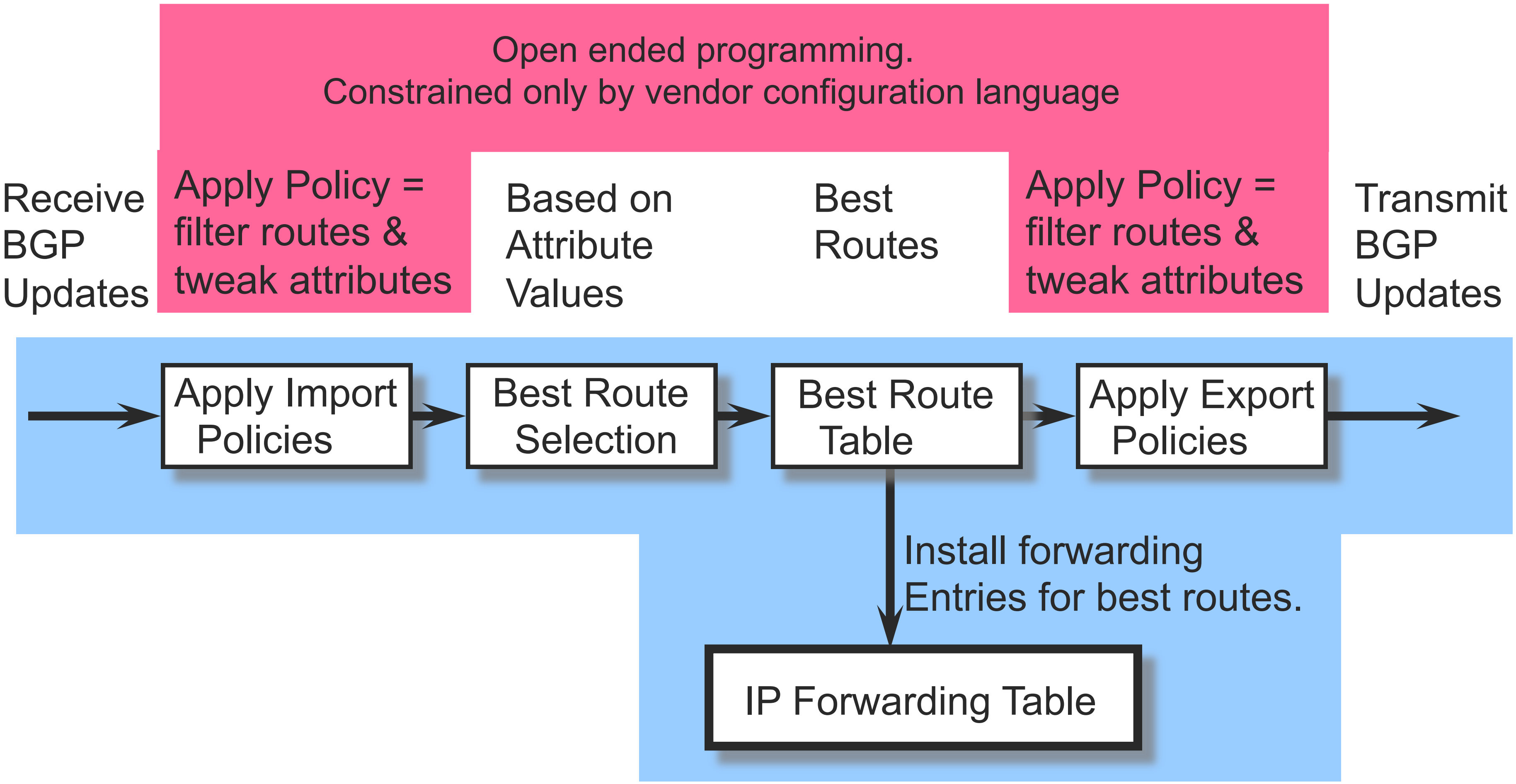
BGP Operations



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 neighbors
  - Withdrawal
    - If the active route is no longer available
    - … send a withdrawal message to the neighbors

BGP Route Processing

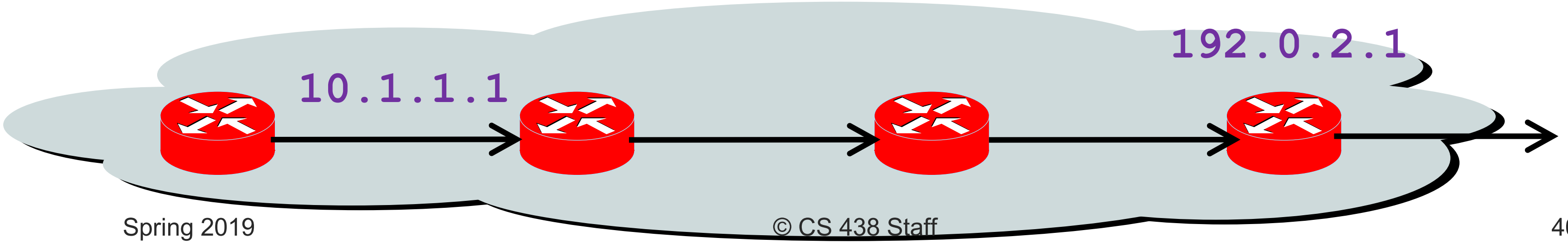


Selecting the best route

- Route Attributes
  - Set/modified according to operator instructions
- Route Choices
  - Compared based on attributes using (mostly) standardized rules

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 `10.1.1.1`



Summary

- BGP is essential to the Internet
  - ties different organizations together
- Poses fundamental challenges....
  - leads to use of path vector approach
- ...and myriad details