CS4450

Computer Networks:
Architecture and Protocols

Lecture 15
Border-Gateway Protocol

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Recap from last lecture

Three requirements for addressing

- **Scalable routing**
  - How must state must be stored to forward packets?
  - How much state needs to be updated upon host arrival/departure?
- **Efficient forwarding**
  - How quickly can one locate items in routing table?
- **Host must be able to recognize packet is for them**

L2 addressing does not enable scalable routing

- **Scalable routing**
  - How much state to forward packets?
    - One entry per host per switch
  - How much state updated for each arrival/departure?
    - One entry per host per switch

- **Efficient forwarding**
  - Exact match lookup on MAC addresses (exact match is easy!)

- **Host must be able to recognize the packet is for them**
  - MAC address does this perfectly

Layer 3: Hierarchical addressing

- Routing tables cannot have entry for each switch in the Internet
- Use addresses of the form — Network:Host
- Routers know how to reach all networks in the world
    - Routing algorithms only announce "Network" part of the addresses
    - Routing tables now store a next-hop for each "network"
- Forwarding:
    - Routers ignore host part of the address
    - When the packet reaches the right network
        - Packet forwarded using Host part of the address
        - Using Layer 2

What do I mean by "network"

- In the original IP addressing scheme …
    - Network meant an L2 network
    - Often referred to as a "subnet"
    - There are too many of them now to scale

Aggregation

- **Aggregation:** single forwarding entry used for many individual hosts

- Example:
    - In our scalable L2 solution: aggregate was switch
    - In our scalable L3 solution: aggregate was network

- Advantages:
    - Fewer entries and more stable
    - Change of hosts do not change tables
        - Don't need to keep state on individual hosts

Hierarchical Structure

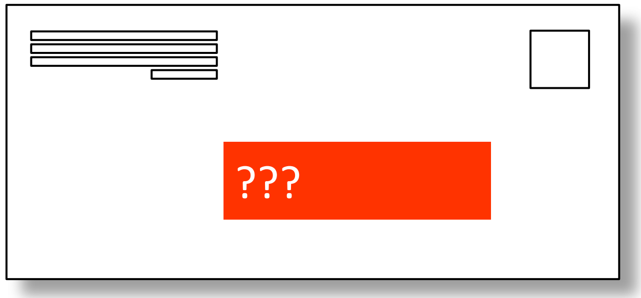
- The Internet is an “inter-network”
    - Used to connect networks together, not hosts

- Forms a natural two-way hierarchy
    - Wide Area Network (WAN) delivers to the right “network”
    - Local Area Network (LAN) delivers to the right host

Hierarchical Addressing

- Can you think of an example?

- Addressing in the US mail
    - Country
    - City, Zip code
    - Street
    - House Number
    - Occupant “Name”



IP addresses

- Unique 32 bit numbers associated with a host
- Use dotted-quad notation, e.g., 128.84.139.5

Country	City, State	Street, Number	Occupant
(8 bits)	(8 bits)	(8 bits)	(8 bits)
10000000	0-1010100	10001011	00000-101
128	84	139	5

Network

Host

Original Addressing mechanism

- First eight bits: network address (/8)
  - Slash notation indicates network address
- Last 24 bits: host address
- Assumed 256 networks were more than enough!!!
  - Now we have millions!

Suppose we want to accommodate more networks

- We can allocate more bits to network address

- Problem?
    - Fewer bits for host names
    - What if some networks need more hosts?

Today's Addressing: CIDR

- Classless Inter-domain Routing
- Idea: Flexible division between network and host addresses
- Prefix is **network address**
- Suffix is **host address**
- **Example:**
    - **128.84.139.5/23 is a 23 bit prefix with:**
    - First 23 bits for network address
    - Next 9 bits for host addresses: maximum 2^9 hosts
- **Terminology: "Slash 23"**

Example for CIDR Addressing

- **128.84.139.5/23 is a 23 bit prefix with 2^9 host addresses**

10000000	0-1010100	10001011	00000-101
128	84	139	5

Network (23 bits) Host (9 bits)

Allocating addresses

- Internet Corporation for Assigned Names and Numbers (ICANN) …
- Allocates large blocks of addresses to Regional Internet Registries
  - E.g., American Registry for Internet Names (ARIN) …
- That allocates blocks of addresses to Large Internet Service Providers (ISP)
- That allocate addresses to individuals and smaller institutions
- Fake example:
  - ICANN -> ARIN -> AT&T -> Cornell -> CS -> Me

Allocating addresses: Fake example

- ICANN gives ARIN several /8s
- ARIN given AT&T one /8, **128.0/8**
  - **Network prefix: 10000000**
- AT&T gives Cornell one /16, **128.84/16**
  - **Network prefix: 10000000 01010100**
- Cornell gives CS one /24, **128.84.139/24**
  - **Network prefix: 10000000 01010100 10001011**
- CS given me a specific address **128.84.139.5**
  - **Network prefix: 10000000 01010100 10001011 00000101**

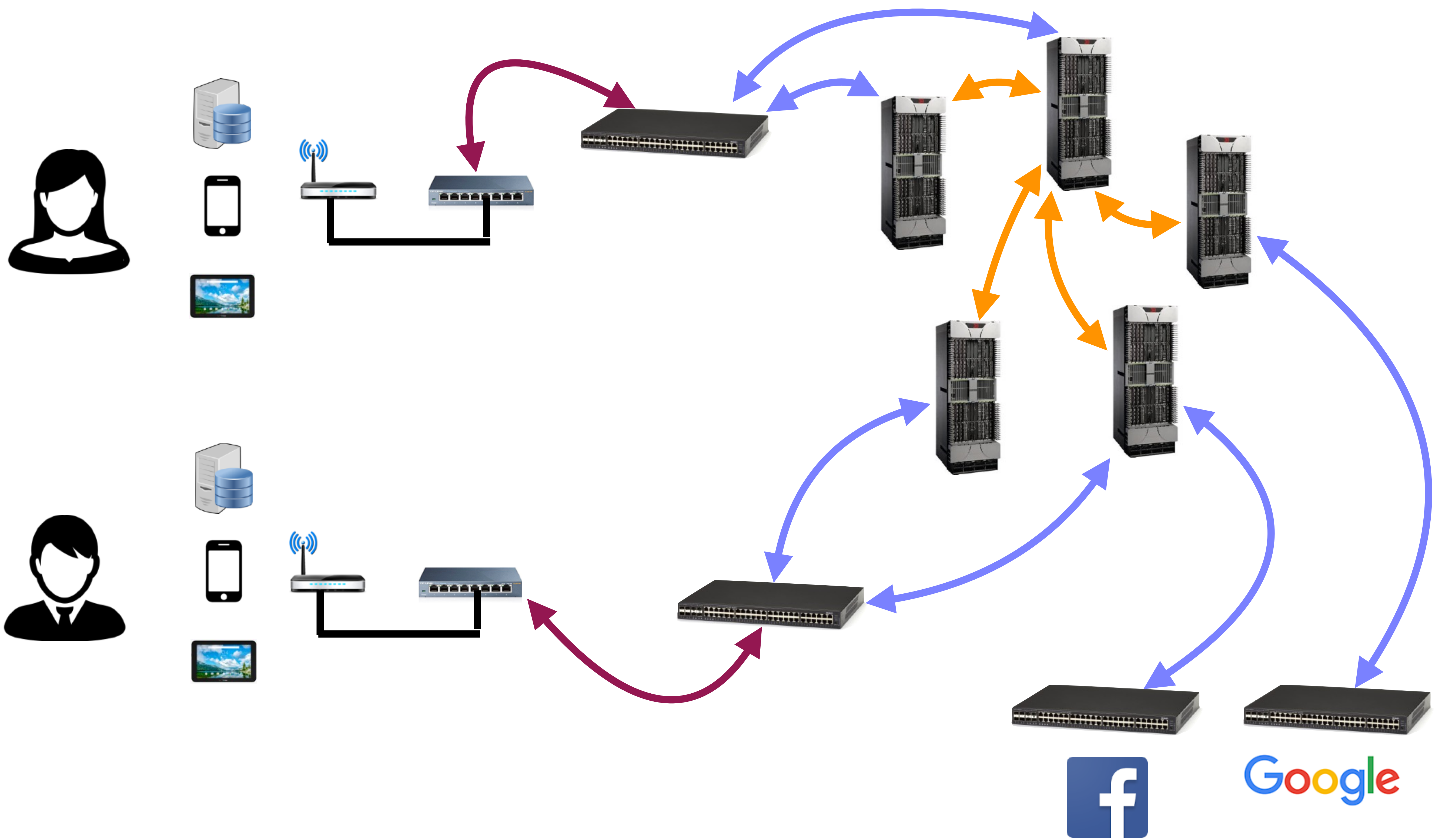
How does this meet our requirements?

- To understand this, we need to understand the routing on the Internet

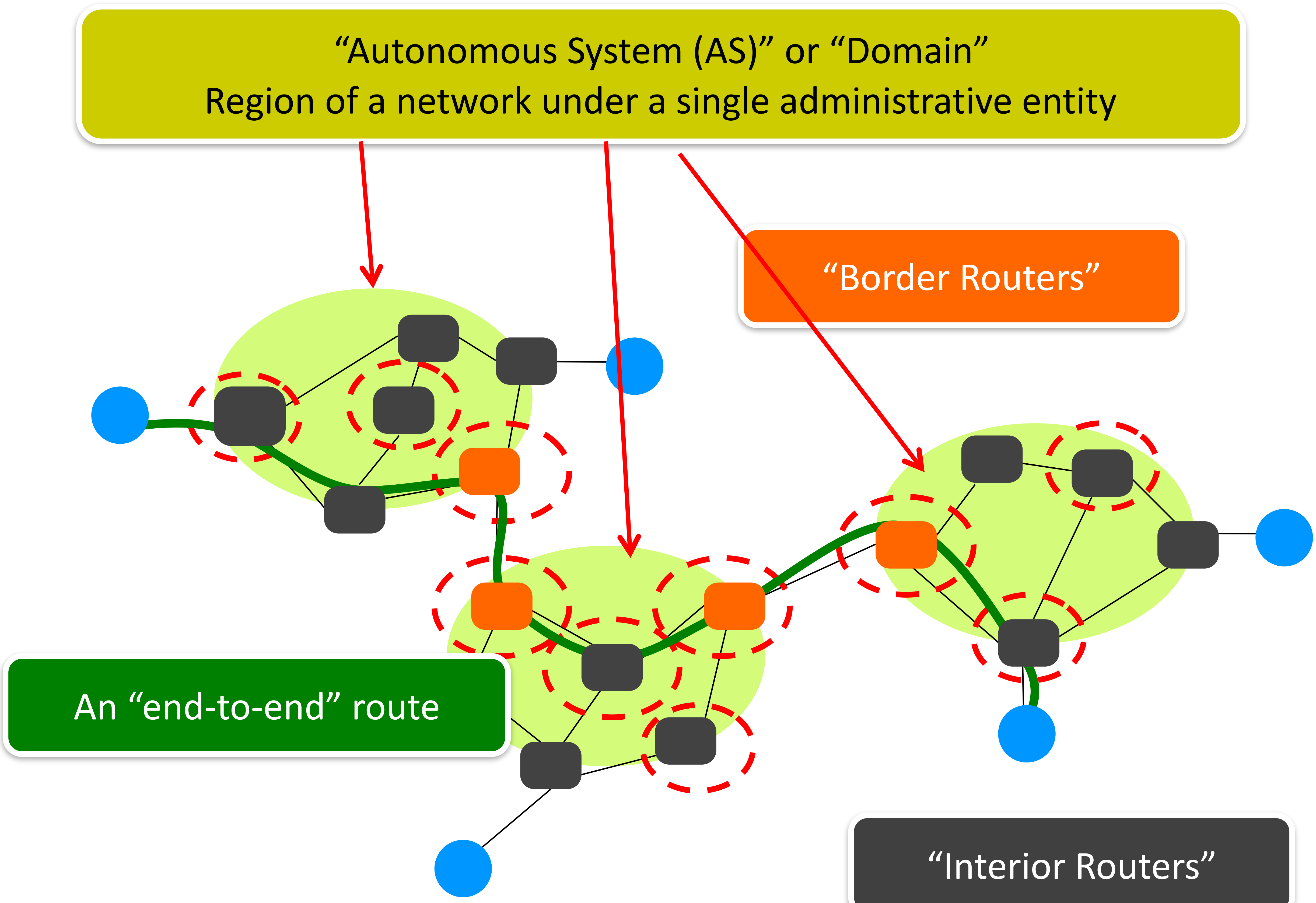
- And to understand that, we need to understand the Internet

Back to the basics: what is a computer network?

A set of network elements connected together, that implement a set of protocols for the purpose of sharing resources at the end hosts



What does a computer network look like?



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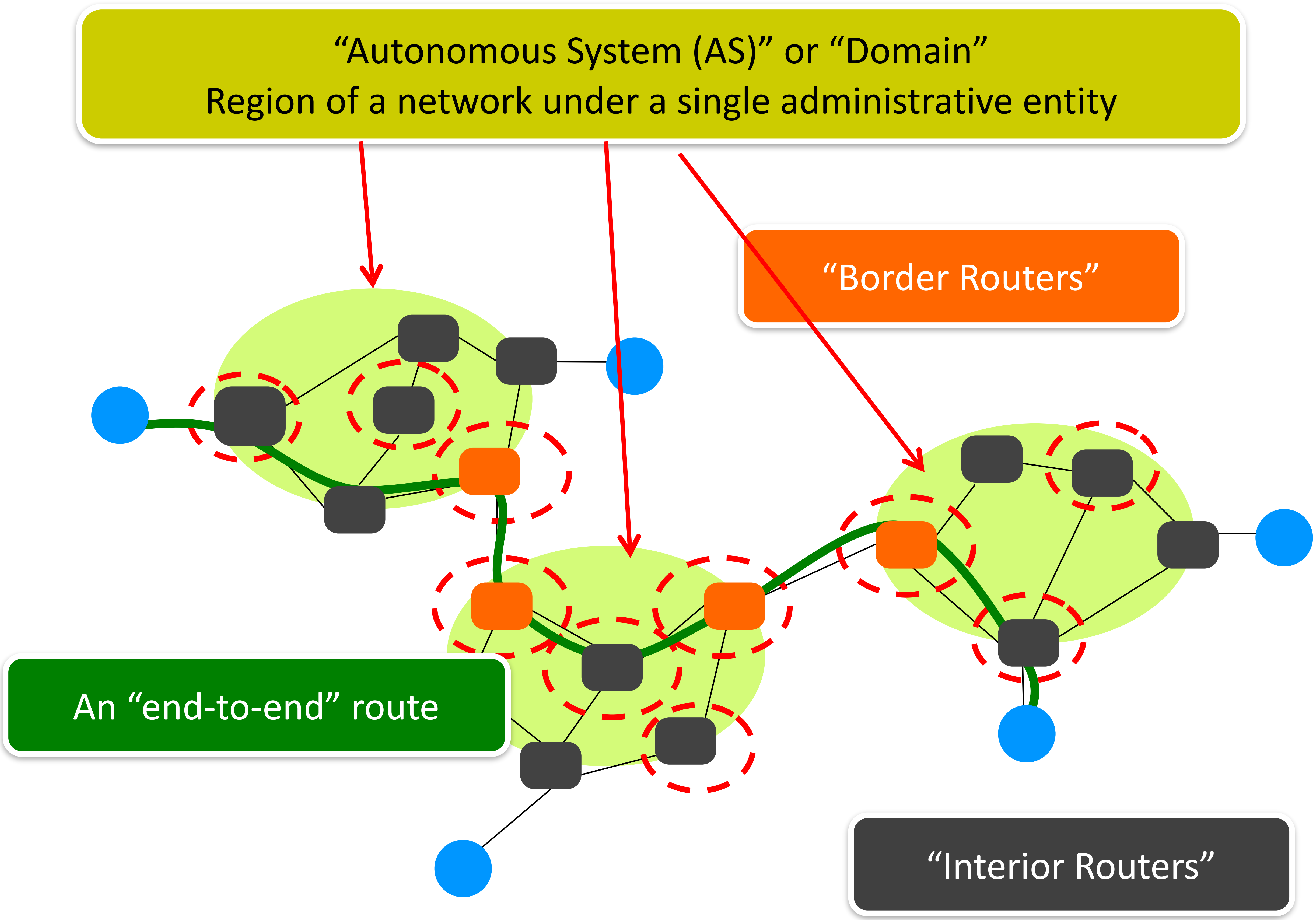


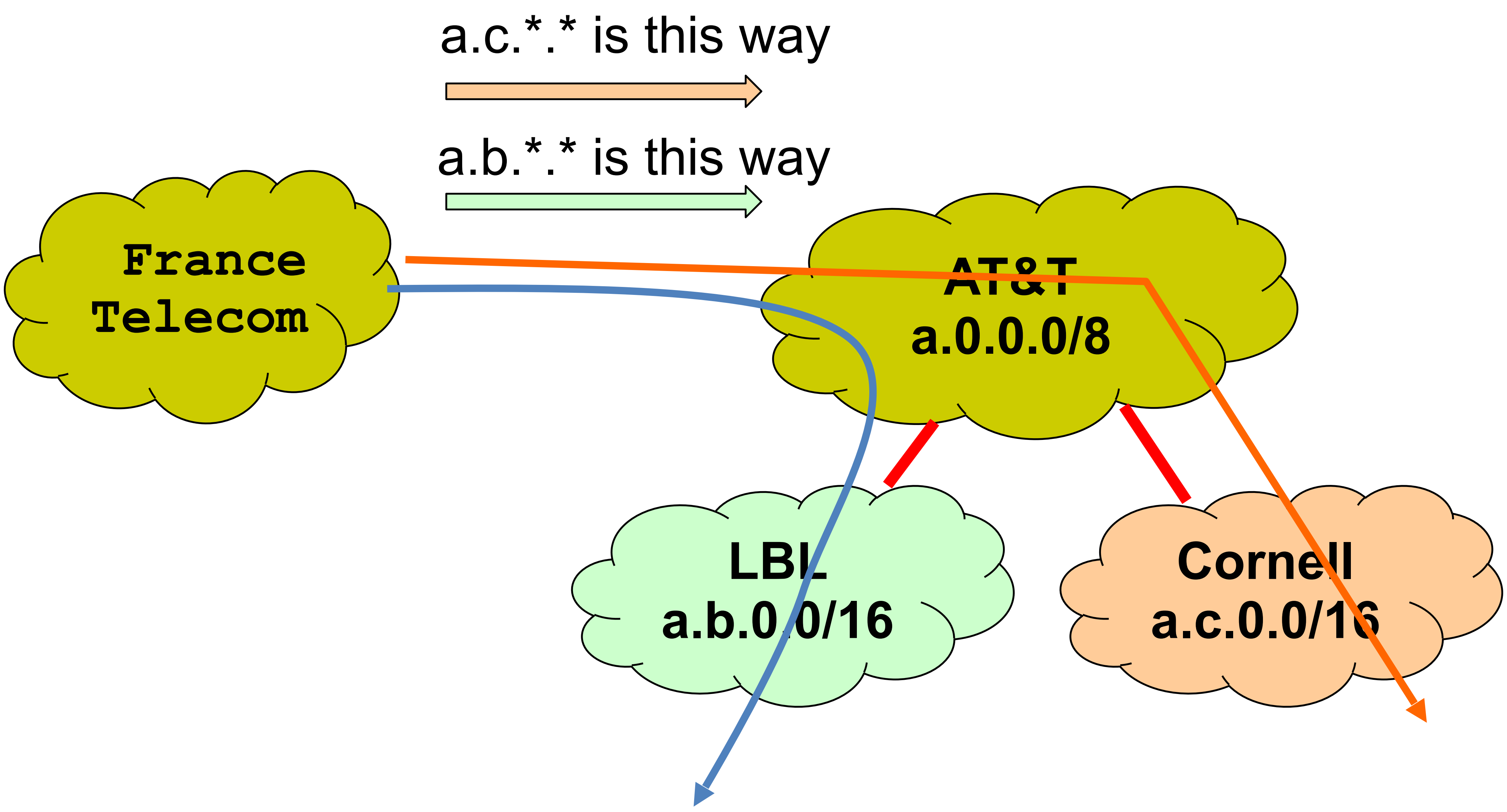
Autonomous Systems (AS)

- An AS is a network under a single administrative control
  - Currently over 30,000
  - **Example: AT&T, France Telecom, Cornell, IBM, etc.**
  - A collection of routers interconnecting multiple switched Ethernets
  - And interconnections to neighboring ASes

- Sometimes called “Domains”

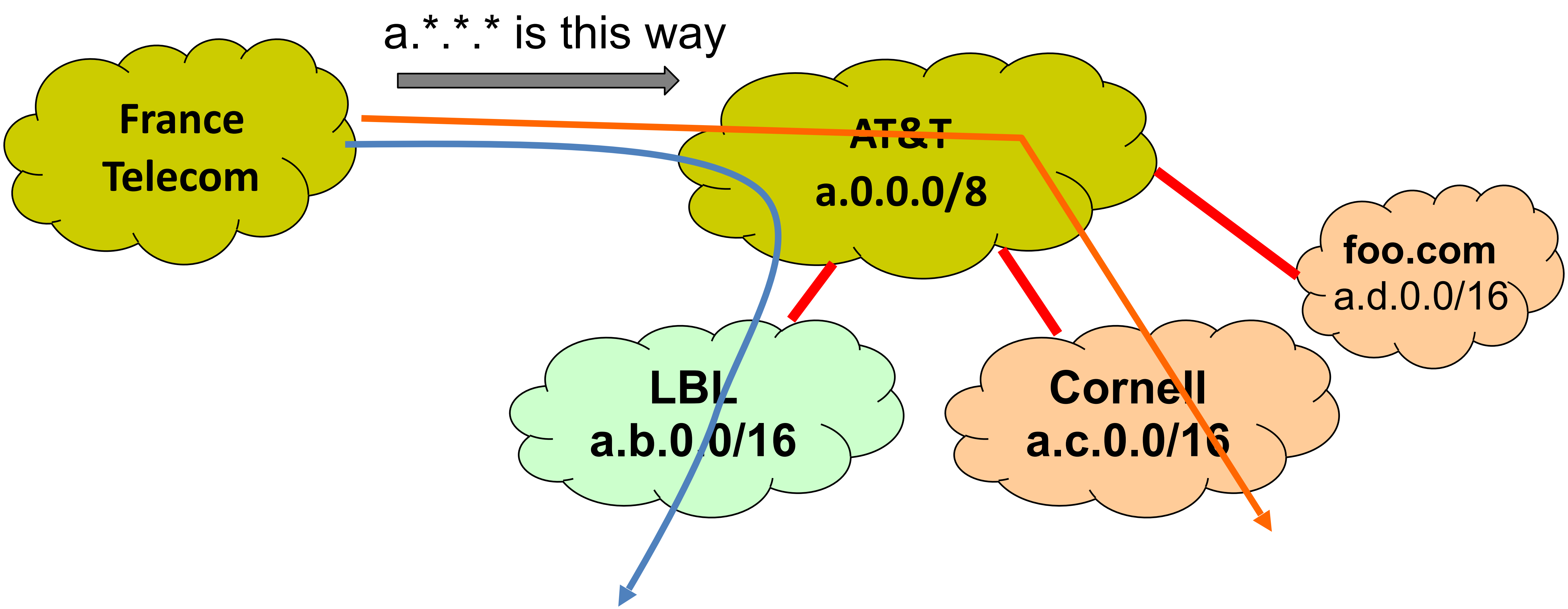
- Each AS assigned a unique identifier
  - **16 bit AS number**

IP addressing -> Scalable Routing?



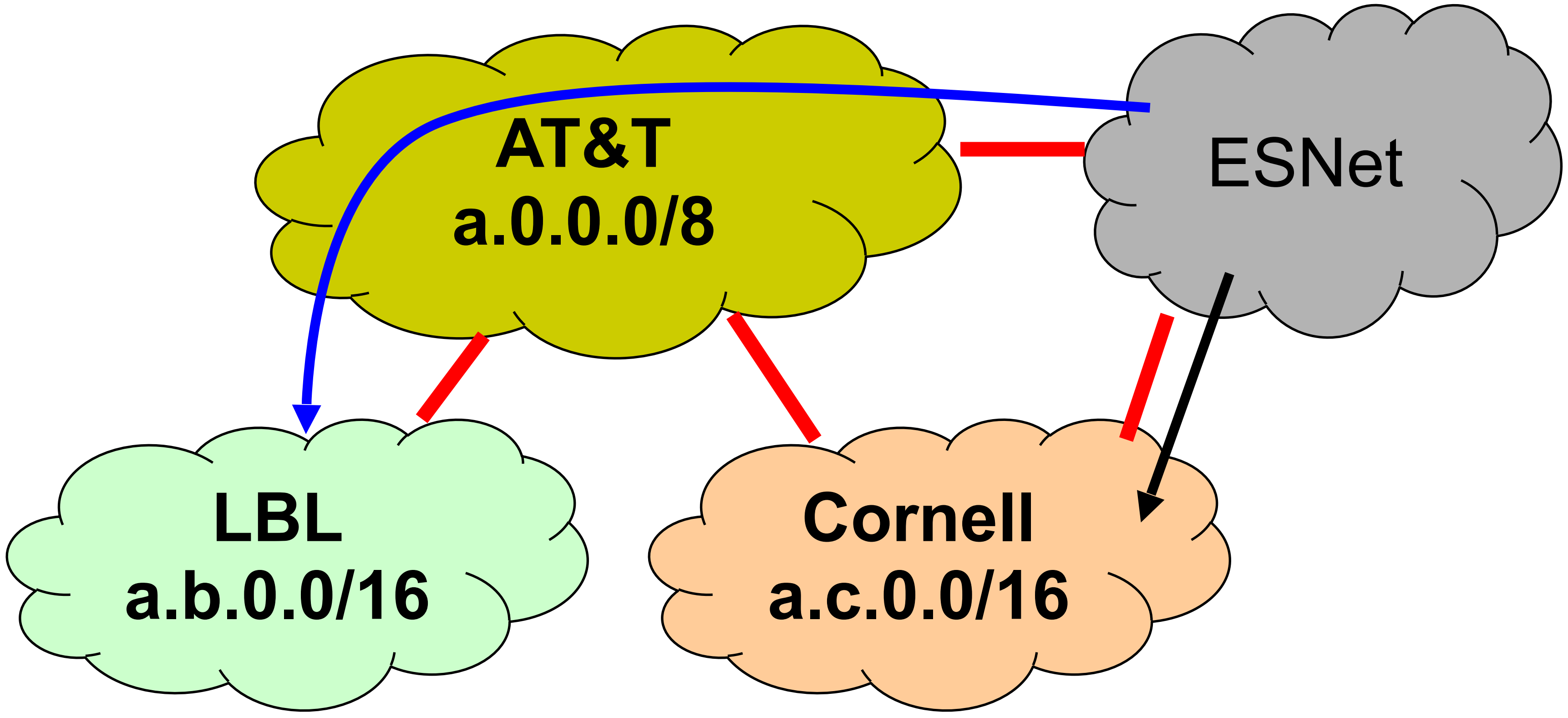
IP addressing -> Scalable Routing?

Can add new hosts/networks without updating the routing entries at France Telecom



IP addressing -> Scalable Routing?

ESNet must maintain routing entries for both a.*.*.* and a.c.*.*



Administrative Structure Shapes Inter-domain Routing

- ASes want freedom to pick routes based on policy
  - *"My traffic can't be carried over my competitor's network!"*
  - *"I don't want to carry A's traffic through my network!"*
  - Cannot be expressed as Internet-wide "least cost"

- ASes want autonomy
  - Want to choose their own internal routing protocol
  - Want to choose their own policy

- ASes want privacy
  - Choice of network topology, routing policies, etc.

Choice of Routing Algorithm

- Link State (LS) vs. Distance Vector (DV)

- LS offers no privacy — broadcasts all network information
- LS limits autonomy — need agreement on metric, algorithm

- DV is a decent starting point
  - Per-destination updates by intermediate nodes give us a hook
  - But, wasn't designed to implement policy
  - … and is vulnerable to loops if shortest paths not taken

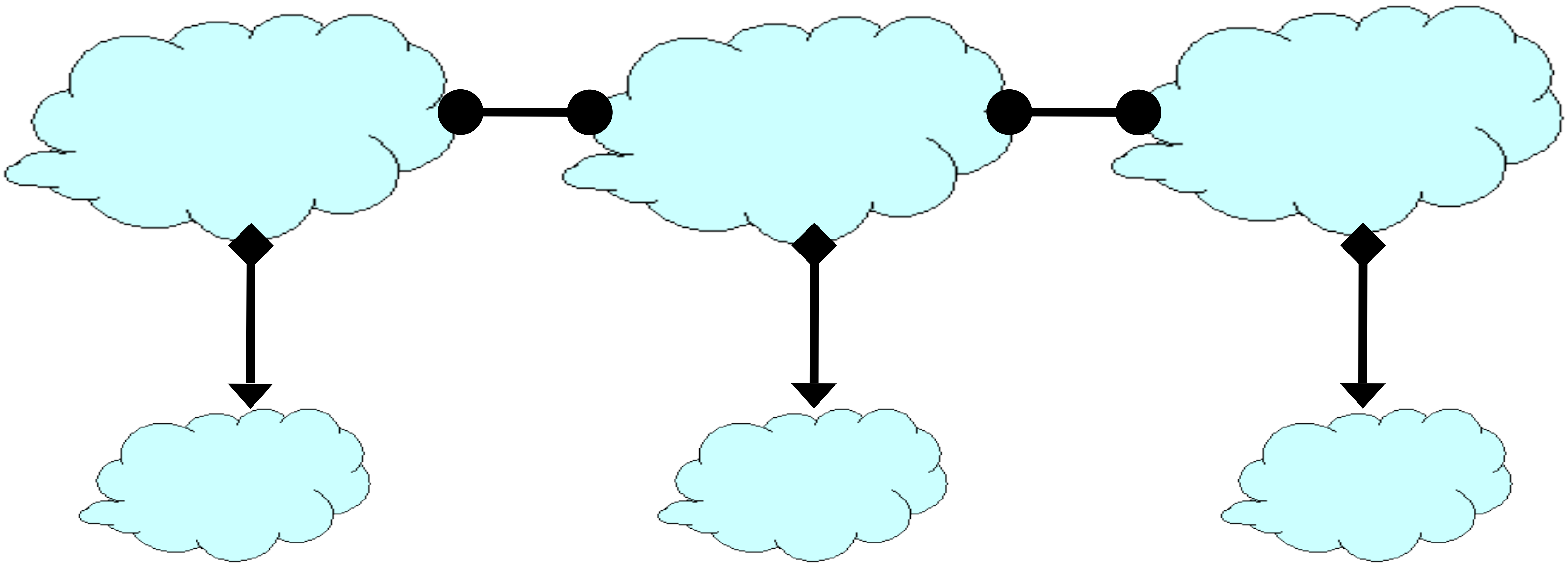
The "Border Gateway Protocol" (BGP) extends Distance-Vector ideas to accomodate policy

Business Relationships Shape Topology and Policy

- Three basic kinds of 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
    - Exchange roughly equal traffic

Business Relationships



Relations between ASes

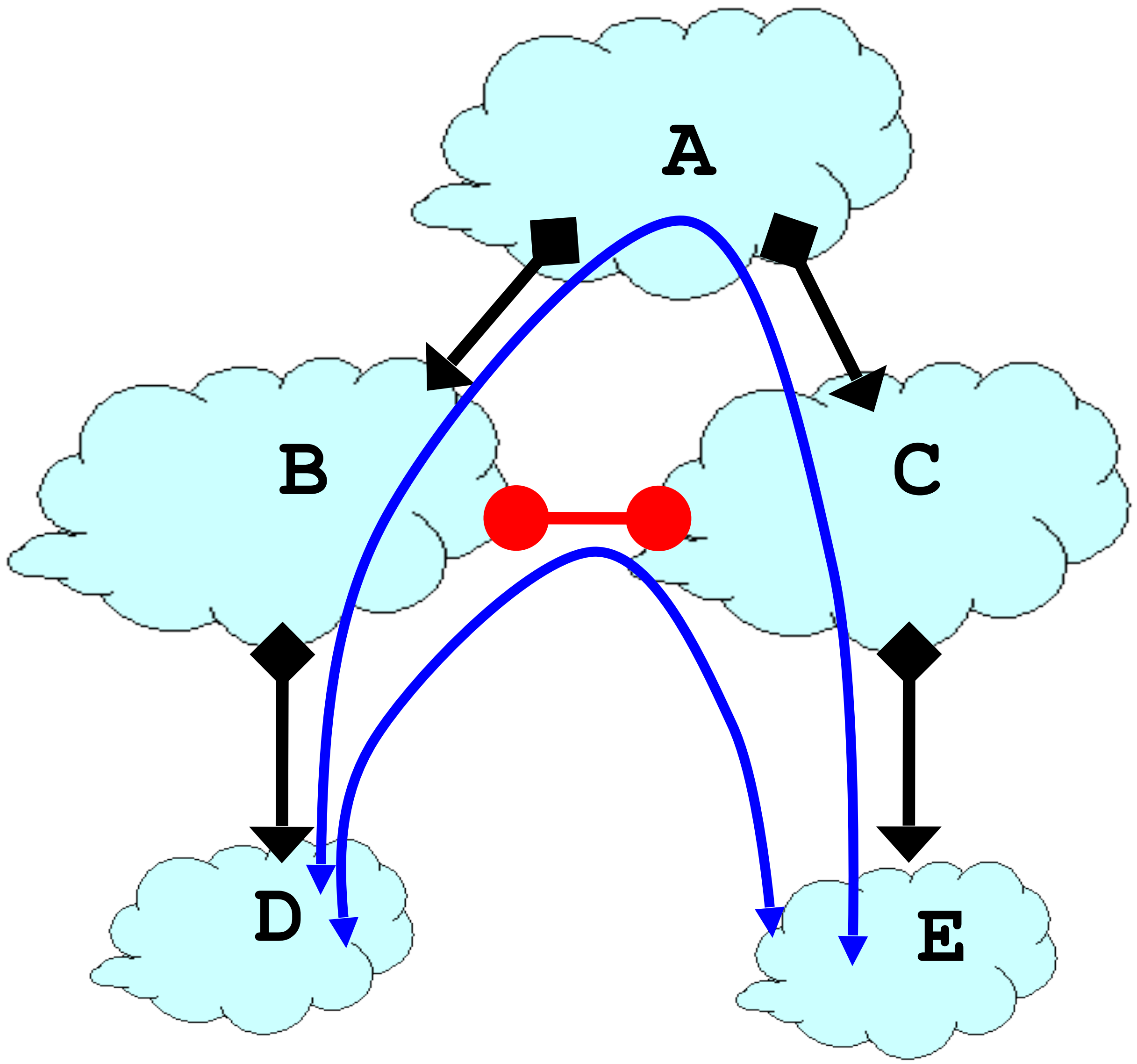
provider ⟷ **customer**

peer ●—● **peer**

Business Implications

- **Customers pay provider**
- **Peers don’t pay each other**

Why Peer?



E.g., D and E talk a lot

Peering saves B *and* C money

Relations between ASes

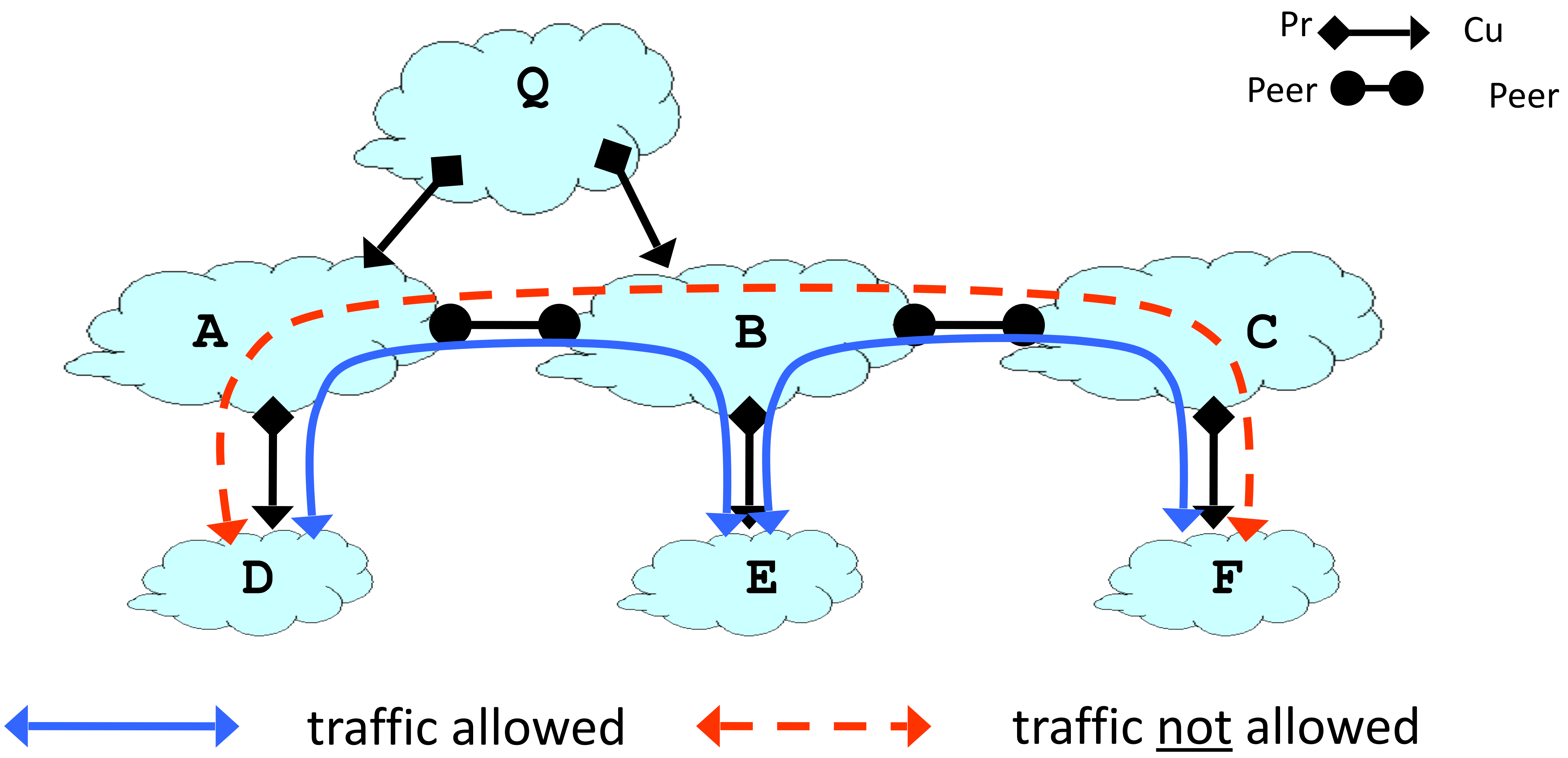
provider ◆———▶ customer

peer ●———● peer

Business Implications

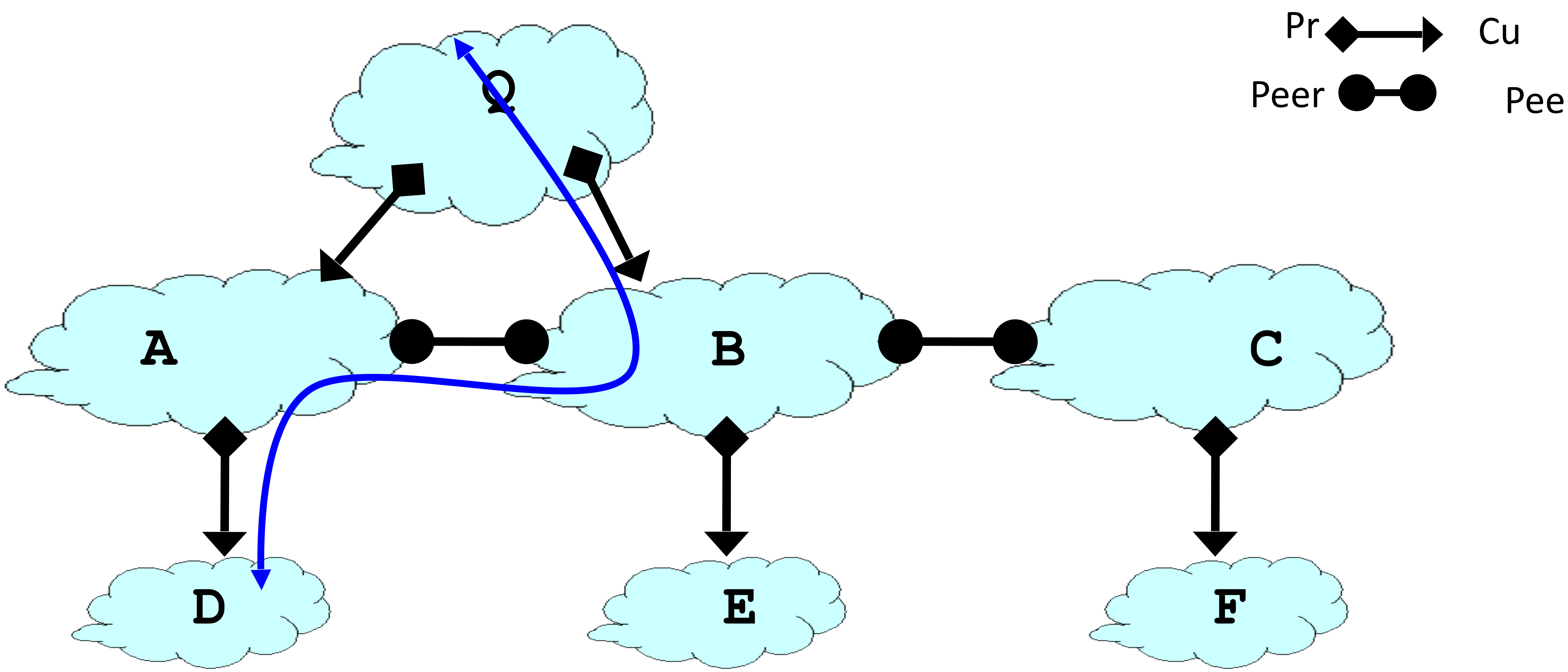
- Customers pay provider
- Peers don't pay each other

Routing Follows the Money



- ASes provide "transit" between their customers
- Peers do not provide transit between other peers

Routing Follows the Money



- An AS only carries traffic to/from its own customers over a peering link

Inter-domain Routing: Setup

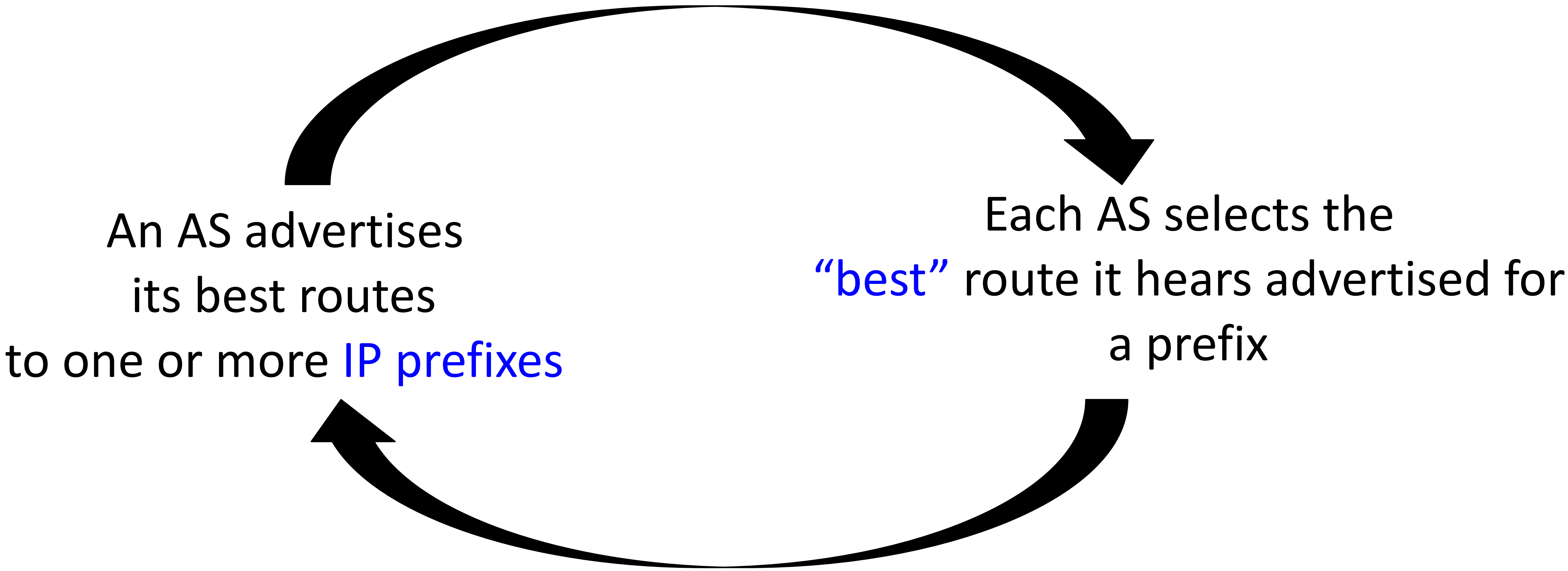
- Destinations are IP prefixes (12.0.0.0/8)

- Nodes are Autonomous Systems (ASes)
  - Internals of each AS are hidden

- Links represent both physical links and business relationships

- BGP (Border Gateway Protocol) is the Interdomain routing protocol
  - Implemented by AS border routers

BGP



Sound familiar?

BGP Inspired by Distance Vector

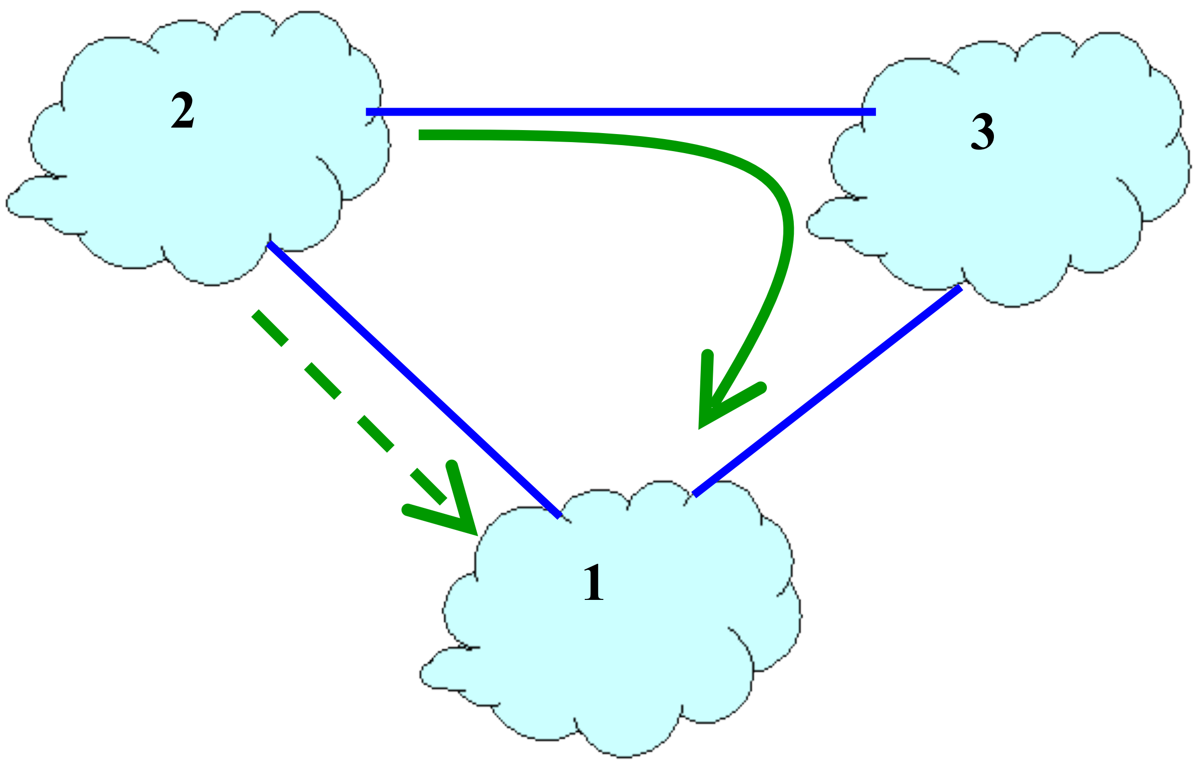
- Per-destination route advertisements
- No global sharing of network topology
- Iterative and distributed convergence on paths
- But, four key differences

BGP vs. DV

(1) BGP does not pick the shortest path routes!

- BGP selects route based on policy, not shortest distance/least cost

Node 2 may prefer 2, 3, 1 over 2, 1

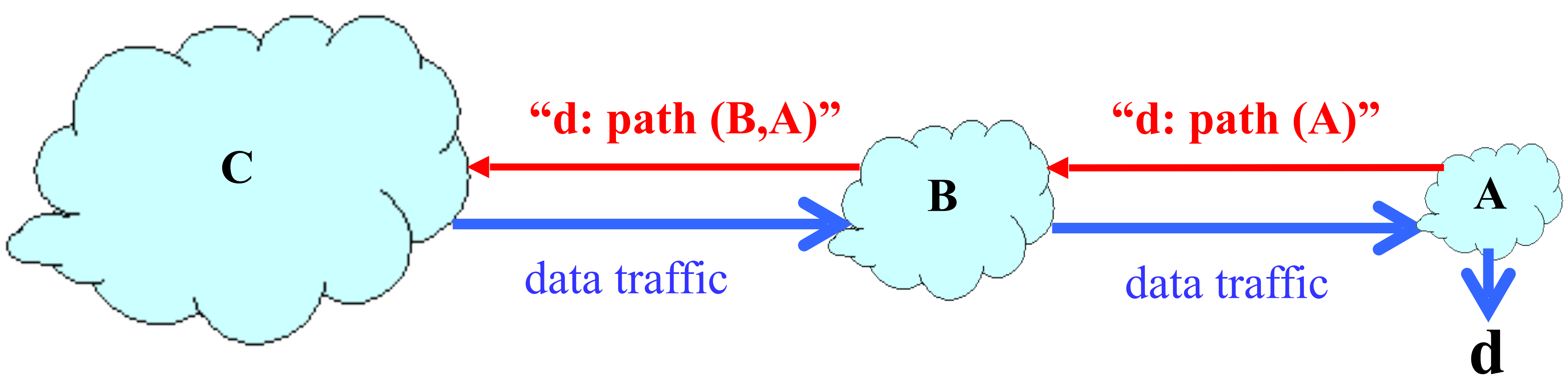


- How do we avoid loops?

BGP vs. DV

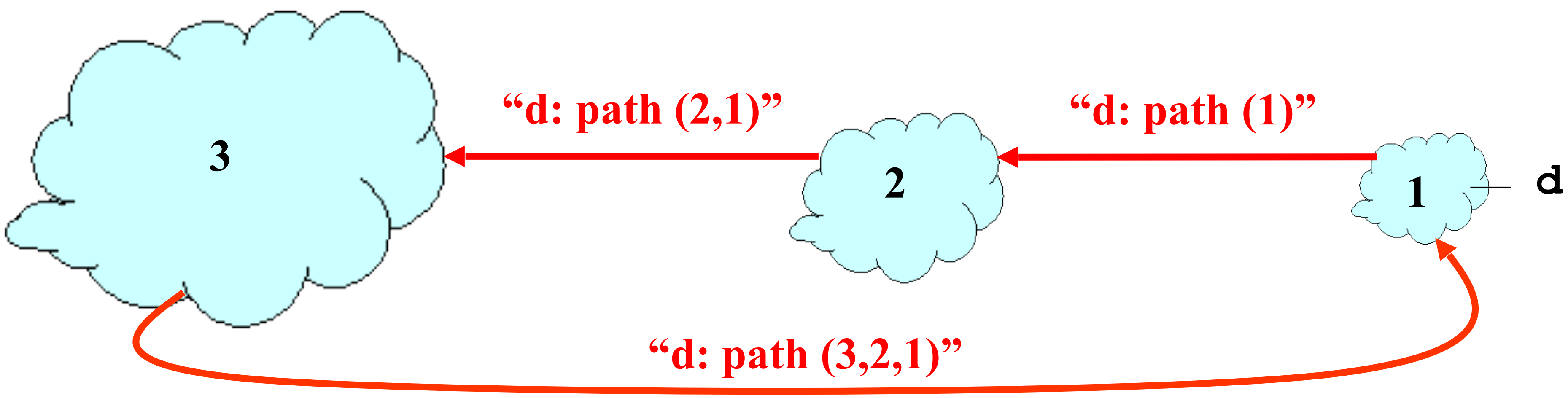
(2) Path-vector Routing

- Idea: advertise the entire path
  - Distance vector: send *distance metric* per dest. d
  - Path vector: send the *entire path* for each dest. d



Loop Detection with Path-Vector

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



BGP vs. DV

(2) Path-vector Routing

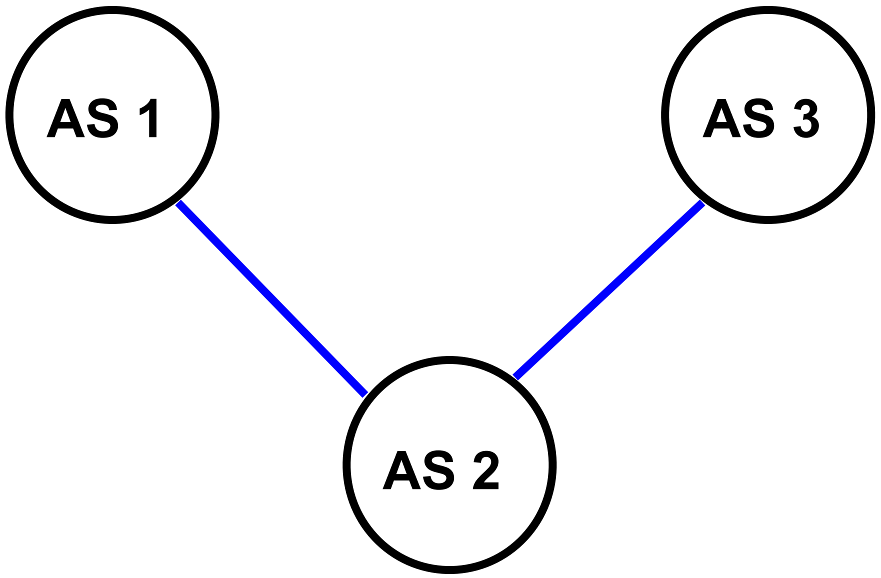
- Idea: advertise the entire path
  - Distance vector: send *distance metric* per dest. d
  - Path vector: send the *entire path* for each dest. d

- Benefits
  - Loop avoidance is easy
  - Flexible policies based on entire path

BGP vs. DV

(3) Selective Route Advertisement

- For policy reasons, an AS may choose not to advertise a route to a destination
- As a result, reachability is not guaranteed even if the graph is connected

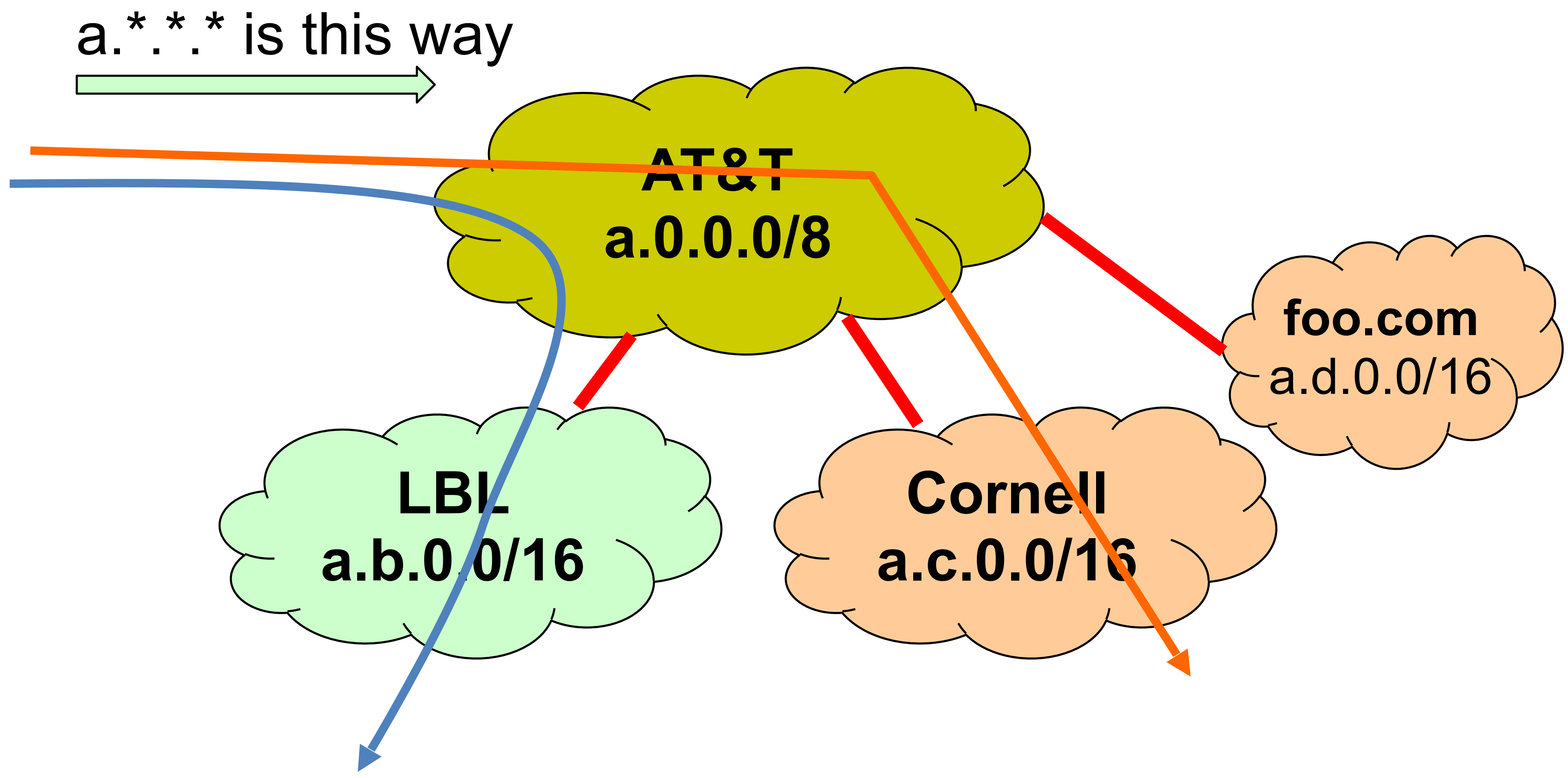


Example: AS#2 does not want to carry traffic between AS#1 and AS#3

BGP vs. DV

(4) BGP may aggregate routes

- For scalability, BGP may aggregate routes for different prefixes

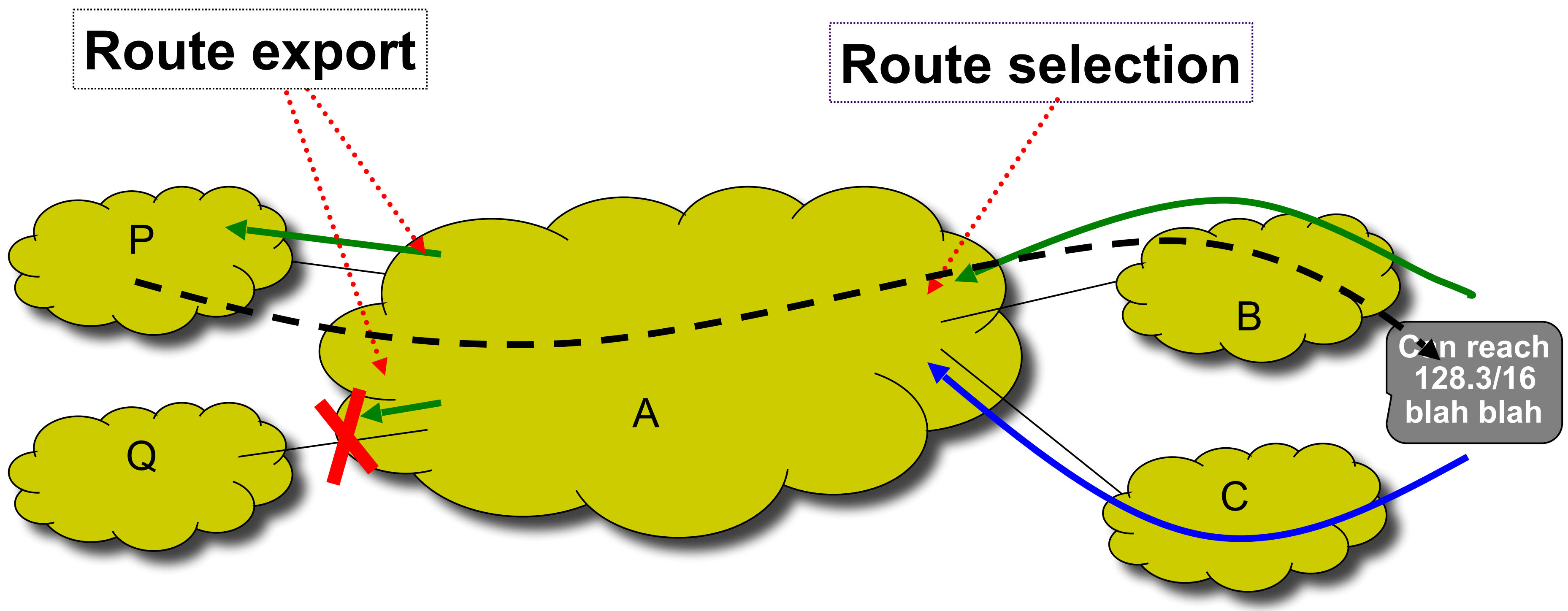


BGP Outline

- BGP Policy
  - Typical policies and implementation
- BGP protocol details
- Issues with BGP

Policy:

Imposed in how routes are selected and exported



- **Selection**: Which path to use
  - Controls whether / how traffic leaves the network
- **Export**: Which path to advertise
  - Controls whether / how traffic enters the network

Typical Selection Policy

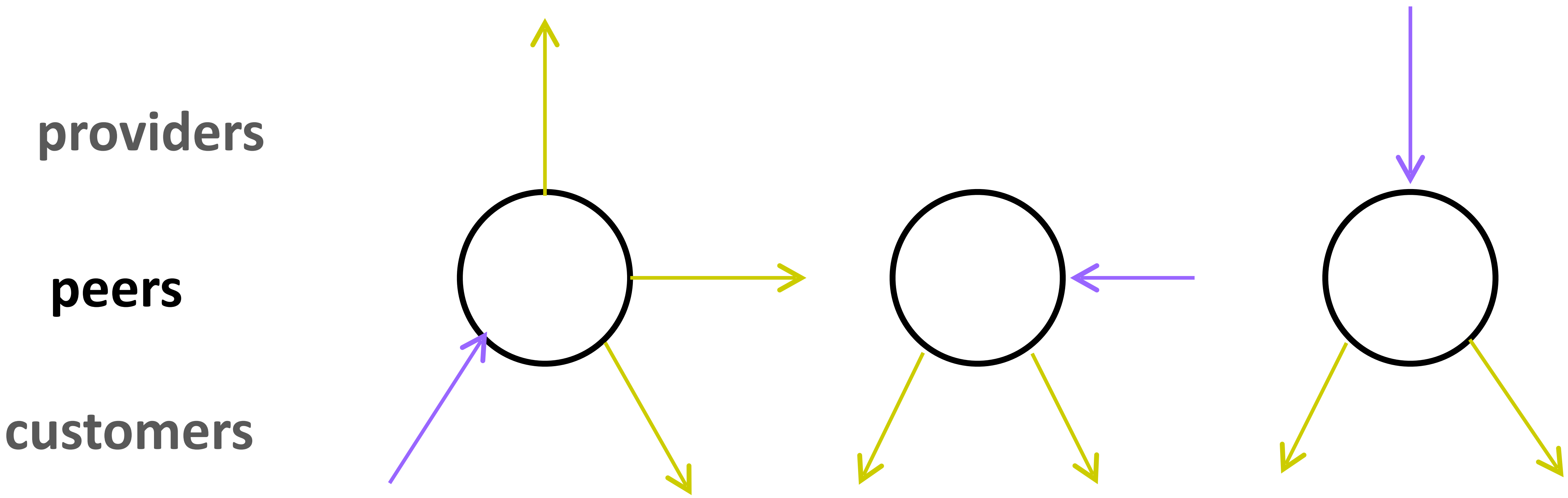
- In decreasing order of priority:
  1. Make or save money (send to customer > peer > provider)
  2. Maximize performance (smallest AS path length)
  3. Minimize use of my network bandwidth (“hot potato”)
  4. …

Typical Export Policy

Destination prefix advertised by…	Export route to…
Customer	Everyone (providers, peers, other customers)
Peer	Customers
Provider	Customers

Known as the "Gao-Rexford" rules
Capture common (but not required!) practice

Gao-Rexford

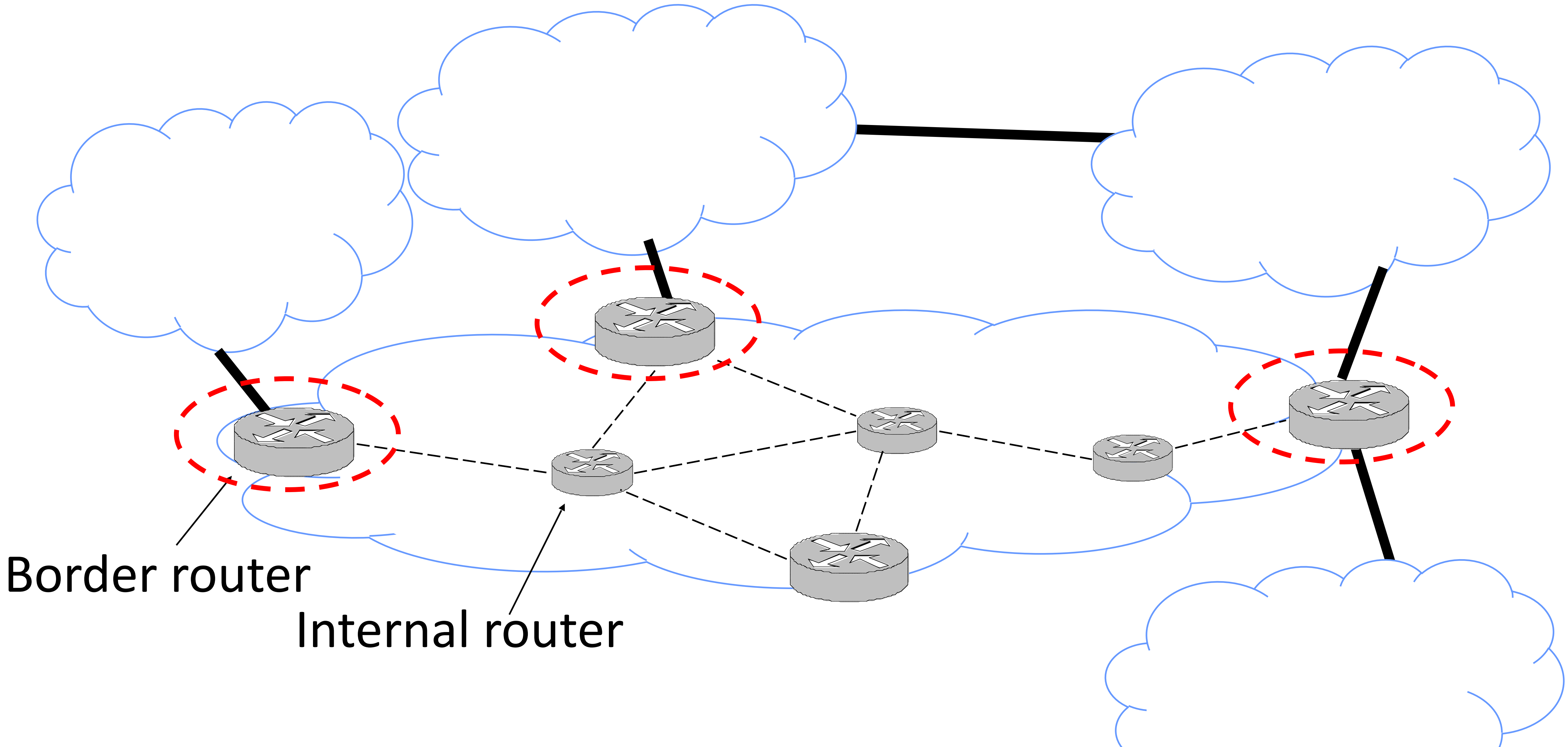


With Gao-Rexford, the AS policy graph is a DAG (directed acyclic graph) and routes are “valley free”

BGP Outline

- BGP Policy
  - Typical policies and implementation
- **BGP protocol details**
- Issues with BGP

Who speaks BGP?



Border routers at an Autonomous System

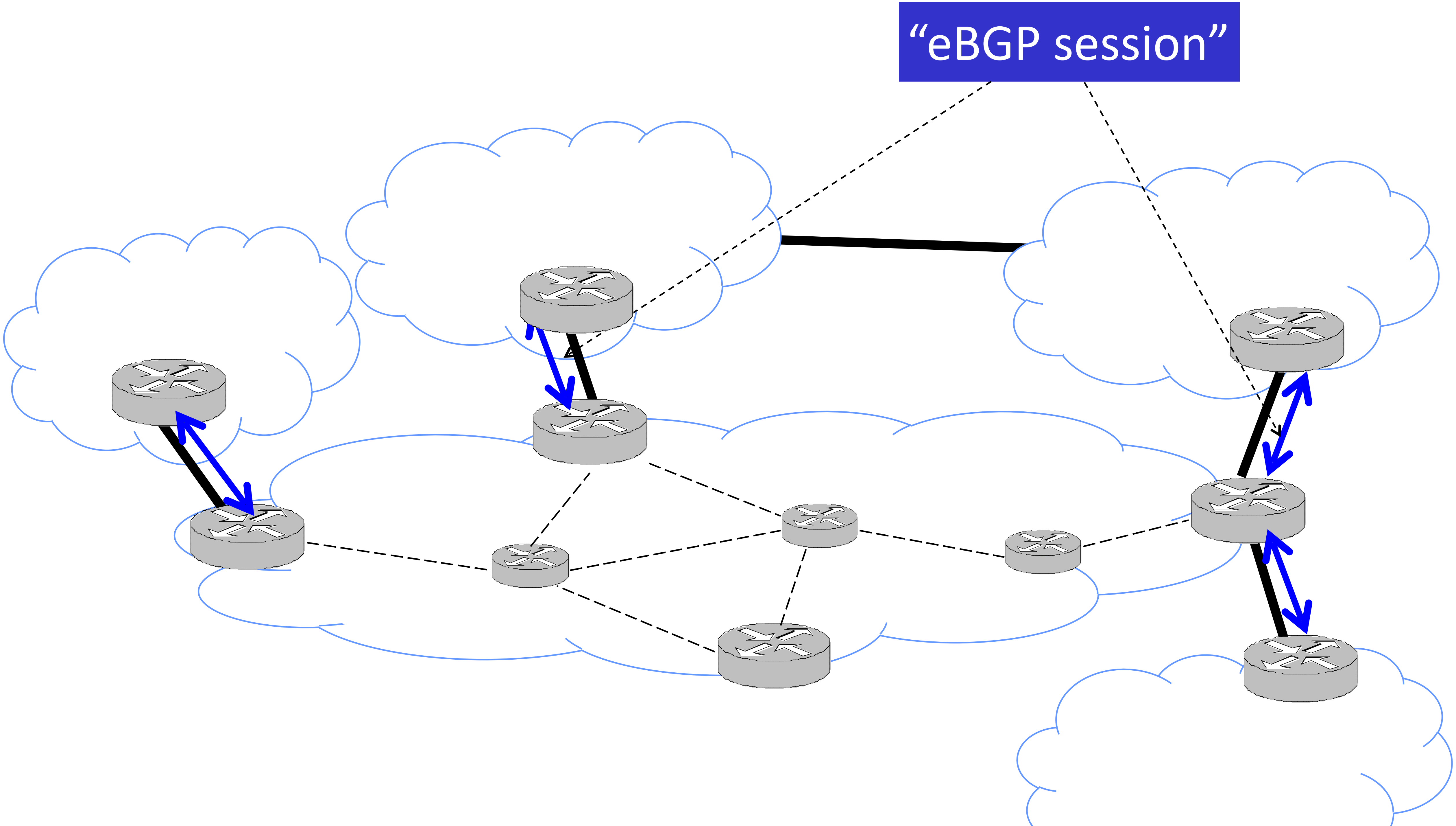
What Does “speak BGP” Mean?

- Implement the BGP Protocol Standard
  - Internet Engineering Task Force (IETF) RFC 4271

- Specifies what messages to exchange with other BGP “speakers”
  - Message types (e.g. route advertisements, updates)
  - Message syntax

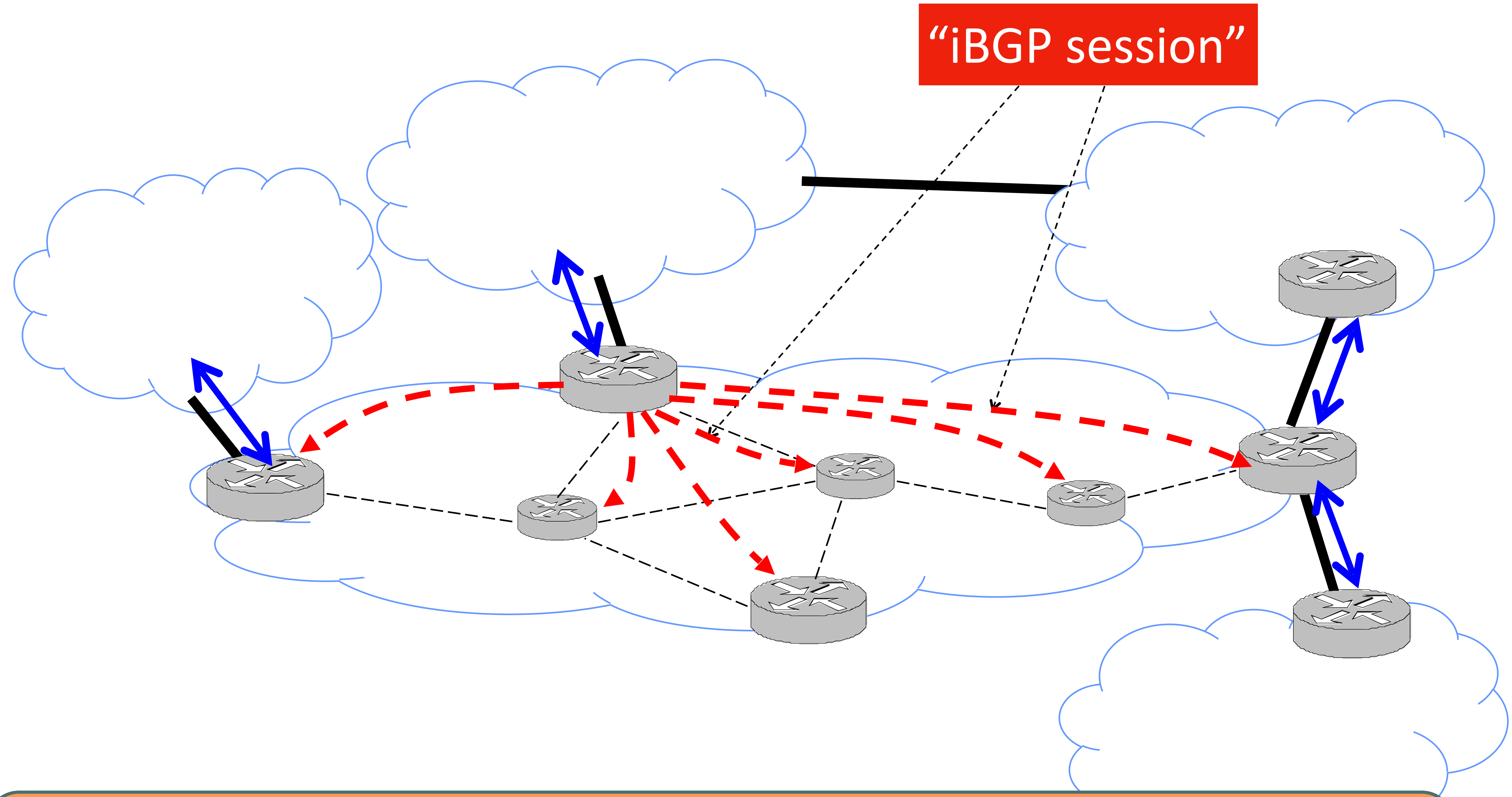
- Specifies how to process these messages
  - When you receive a BGP update, do x
  - Follows BGP state machine in the protocol spec and policy decisions, etc.

BGP Sessions



A border router speaks BGP with border routers in other ASes

BGP Sessions



A border router speaks BGP with other (interior and border) routers in its own AS

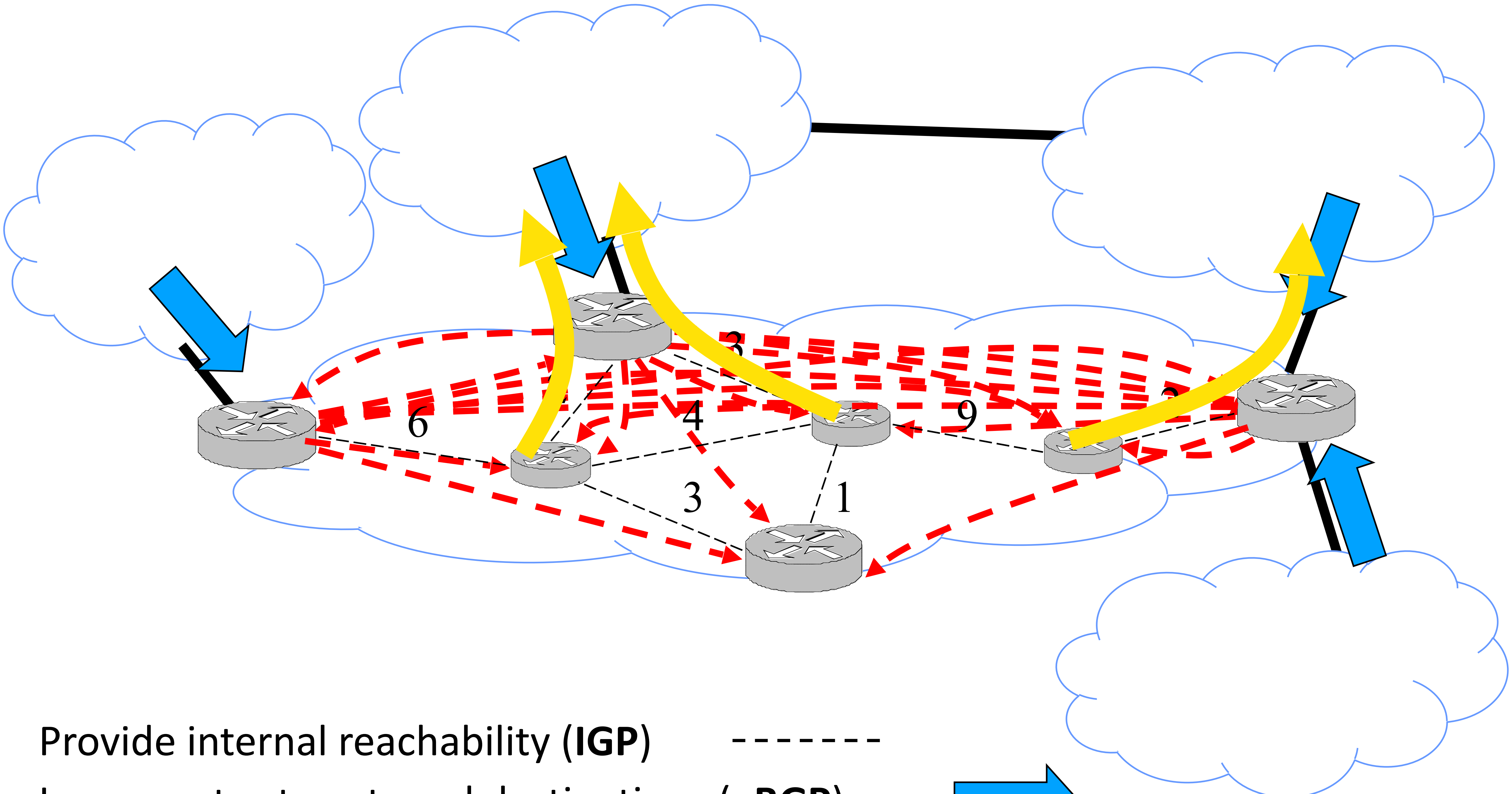
eBGP, iBGP, IGP

- eBGP: BGP sessions between border routers in different ASes
  - Learn routes to external destinations

- iBGP: BGP sessions between border routers and other routers within the same AS
  - Distribute externally learned routes internally

- IGP: Interior Gateway Protocol = Intradomain routing protocol
  - Provides internal reachability
  - e.g. OSPF, RIP

Putting the Pieces Together



1. Provide internal reachability (**IGP**) - - - - - - - -
2. Learn routes to external destinations (**eBGP**)
3. Distribute externally learned routes internally (**iBGP**)
4. Travel shortest path to egress (IGP)

Basic Messages in BGP

- **Open**
  - Establishes BGP session
  - BGP uses TCP
- **Update**
  - Inform neighbor of new routes
  - Inform neighbor of old routes that become inactive
- **Keepalive**
  - Inform neighbor that connection is still viable

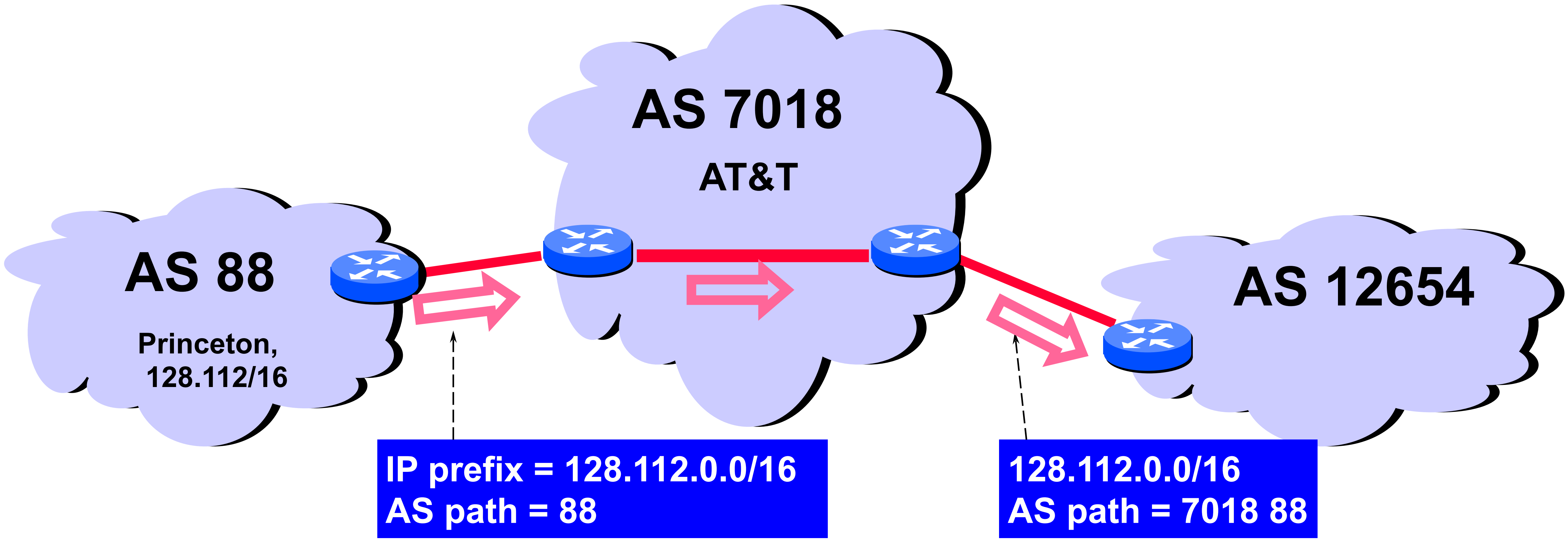
Route Updates

- Format: *<IP prefix: route attributes>*
- Two kinds of updates:
  - Announcements: new routes or changes to existing routes
  - Withdrawals: remove routes that no longer exist

- Route Attributes
  - Describe routes, used in selection/export decisions
  - Some attributes are local
    - i.e. private within an AS, not included in announcements
  - Some attributes are propagated with eBGP route announcements
  - Many standardized attributes in BGP

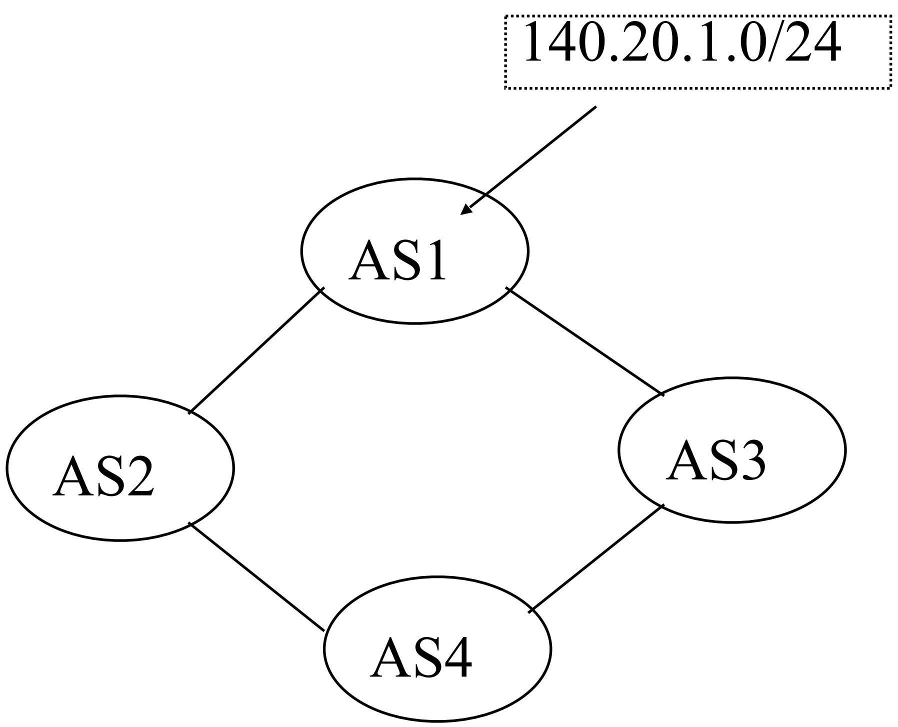
Route Attributes (1): ASPATH

- Carried in route announcements
- Vector that lists all the ASes a route advertisement has traversed (in reverse order)



Route Attributes (2): LOCAL PREF

- "Local Preference"
- Used to choose between different AS paths
- The higher the value, the more preferred
- Local to an AS; carried only in iBGP messages

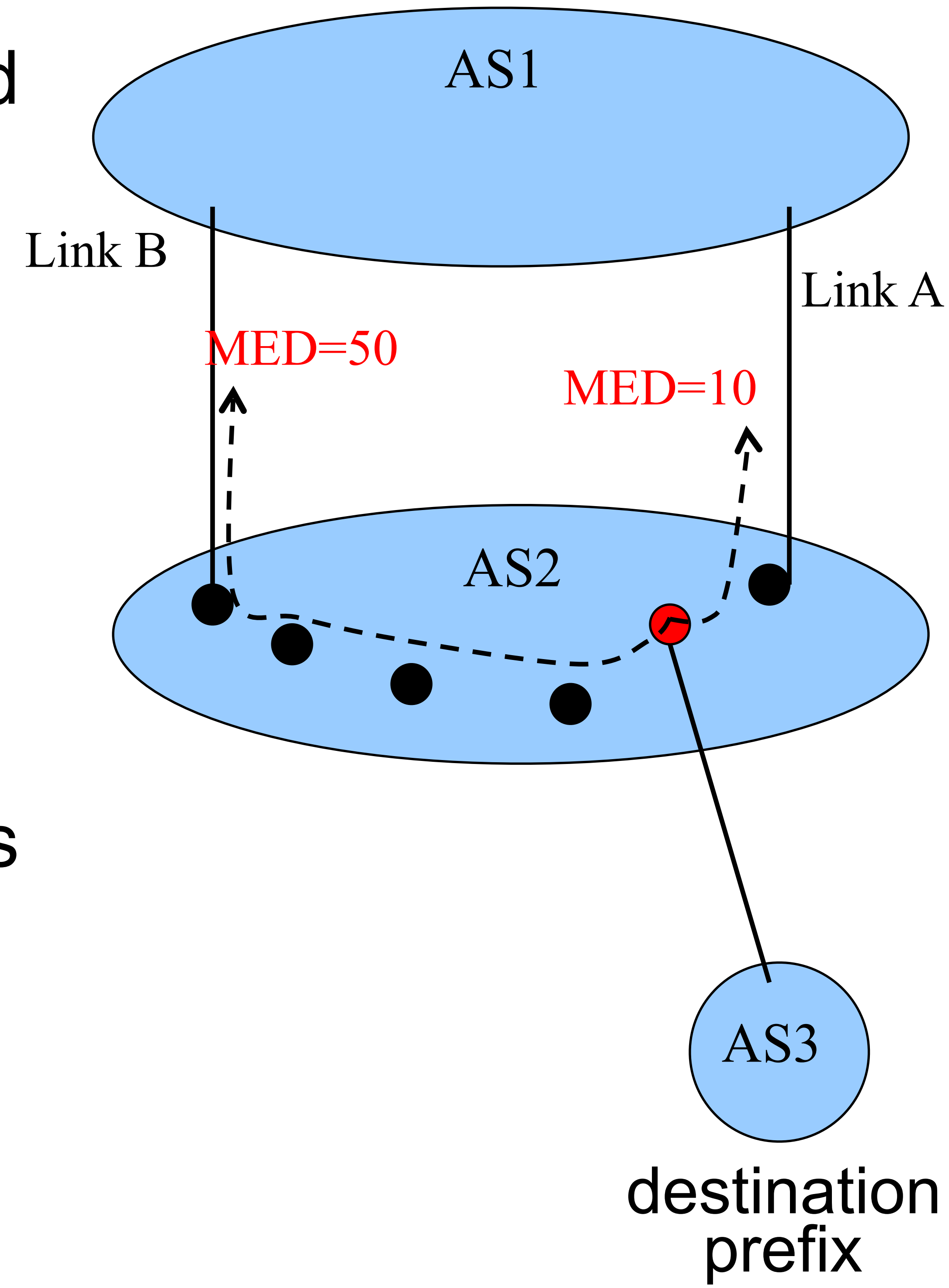


BGP table at AS4:

Destination	AS Path	Local Pref
140.20.1.0/24	AS3 AS1	300
140.20.1.0/24	AS2 AS1	100

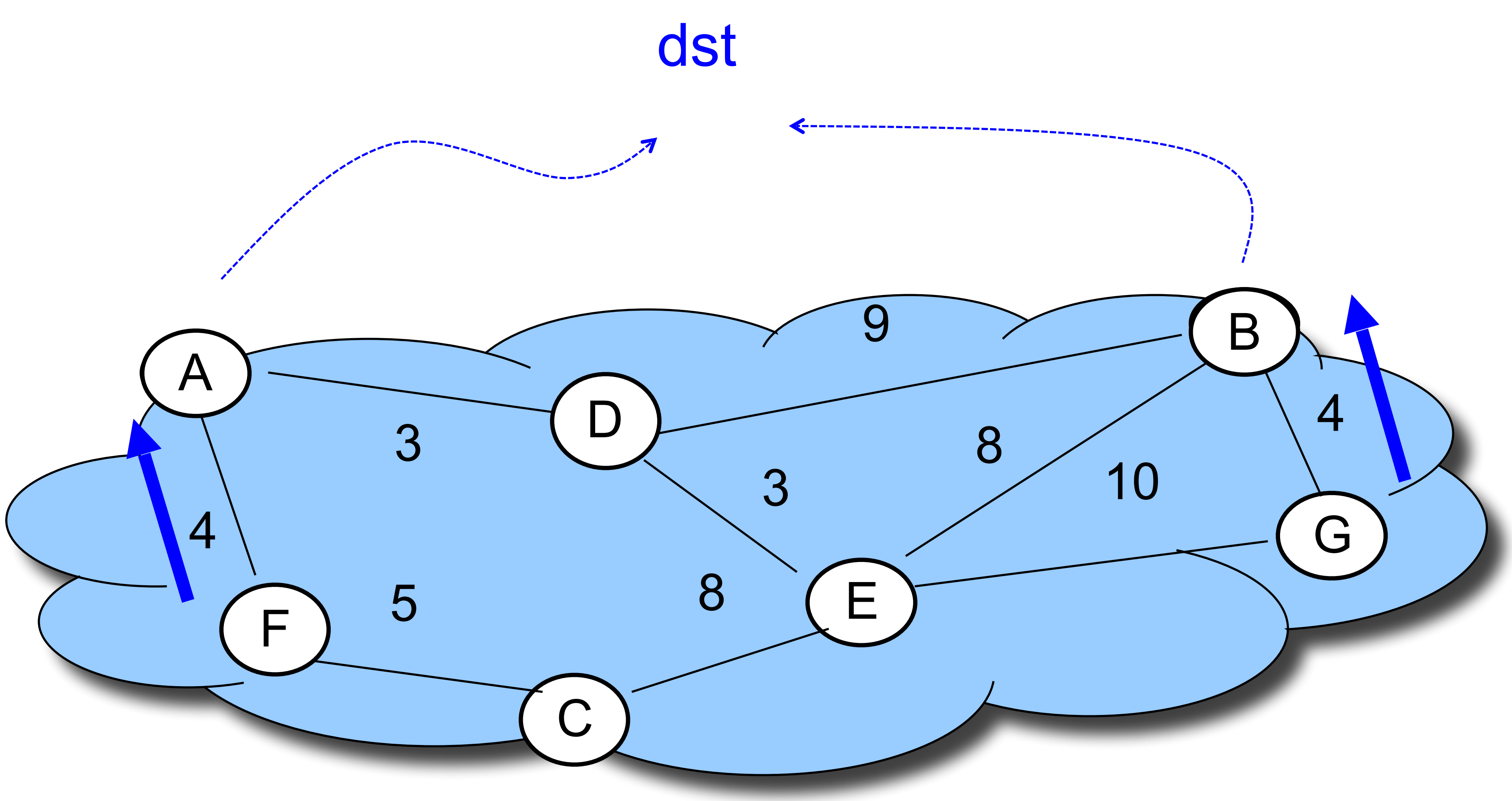
Route Attributes (3) : MED

- "Multi-Exit Discriminator"
- Used when ASes are interconnected via two or more links
  - Specifies how close a prefix is to the link it is announced on
- Lower is better
- AS announcing prefix sets MED
- AS receiving prefix (optionally!) uses MED to select link



Route Attributes (4): IGP Cost

- Used for hot-potato routing
  - Each router selects the closest egress point based on the path cost in intra-domain protocol



Using Attributes

- Rules for route selection in priority order

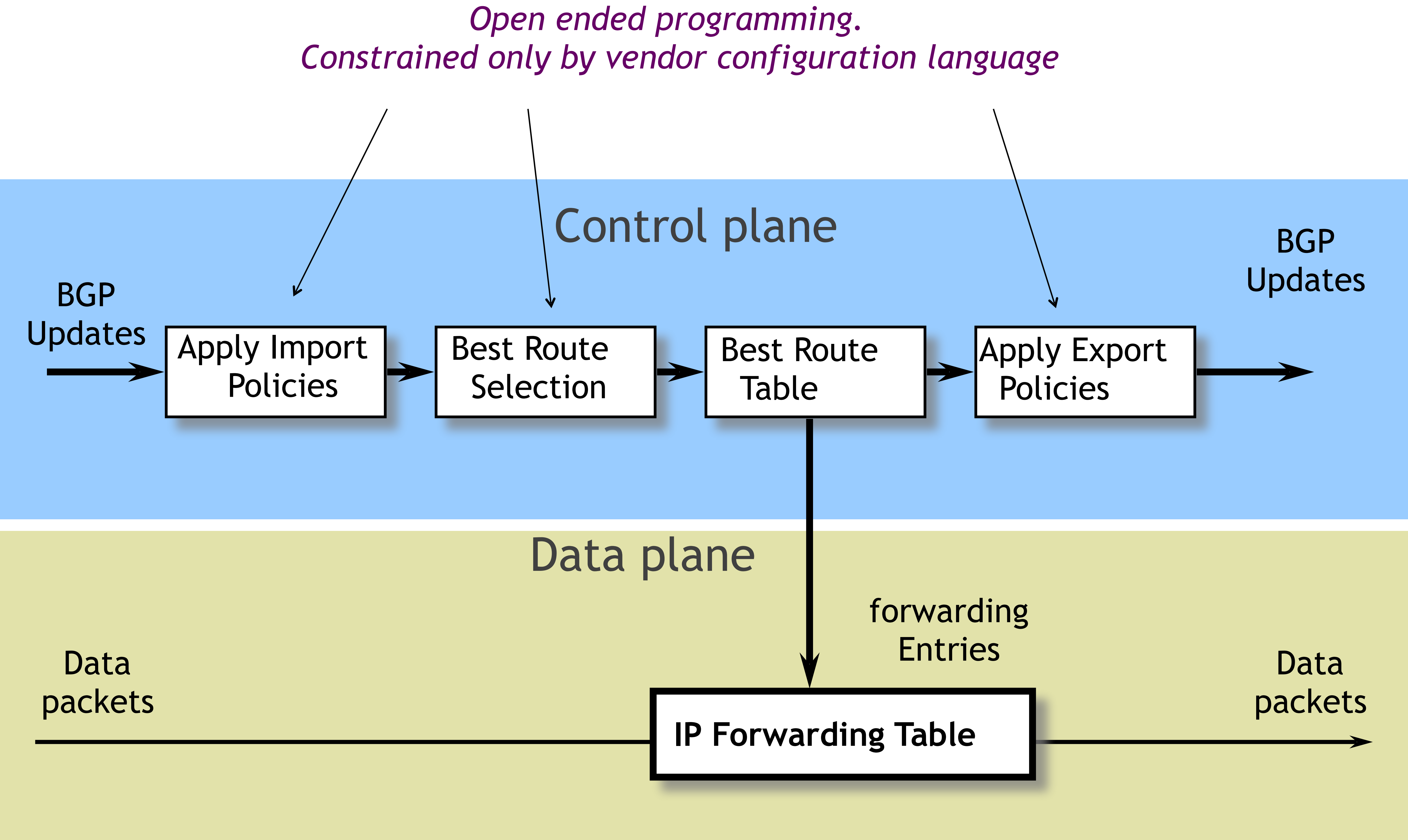
1. Make or save money (send to customer > peer > provider)
2. Maximize performance (smallest AS path length)
3. Minimize use of my network bandwidth (“hot potato”)
4. …

Using Attributes

- Rules for route selection in priority order

Priority	Rule	Remarks
1	`LOCAL PREF`	Pick highest `LOCAL PREF`
2	`ASPATH`	Pick shortest `ASPATH` length
3	`MED`	Lowest `MED` preferred
4	eBGP > iBGP	Did AS learn route via eBGP (preferred) or iBGP?
5	iBGP path	Lowest IGP cost to next hop (egress router)
6	Router ID	Smallest next-hop router’s IP address as tie-breaker

BGP Update Processing



BGP Outline

- BGP Policy
  - Typical policies and implementation

- BGP protocol details

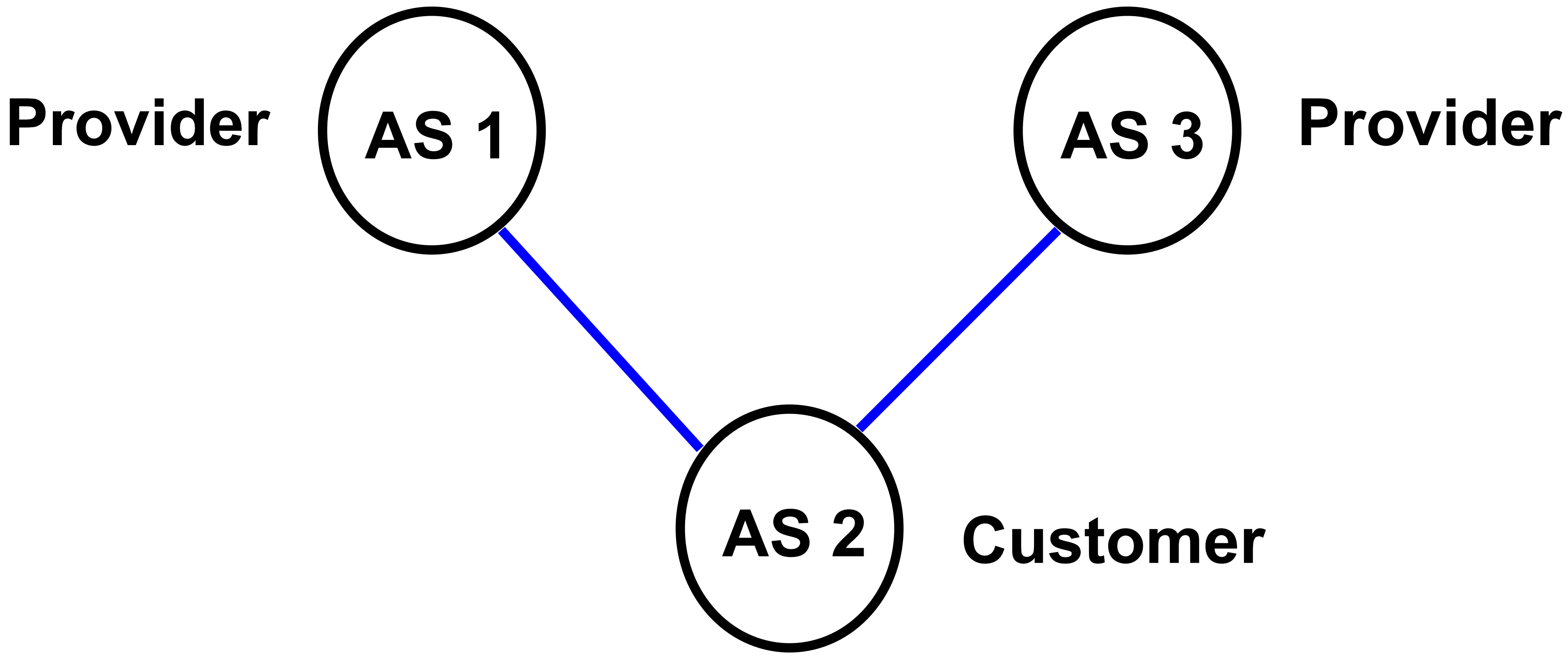
- **Issues with BGP**

BGP: Issues

- Reachability
- Security
- Convergence
- Performance
- Anomalies

Reachability

- In normal routing, if graph is connected then reachability is assured
- With policy routing, this doesn't 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
  - *Fixable: make ASes prove they have a path*

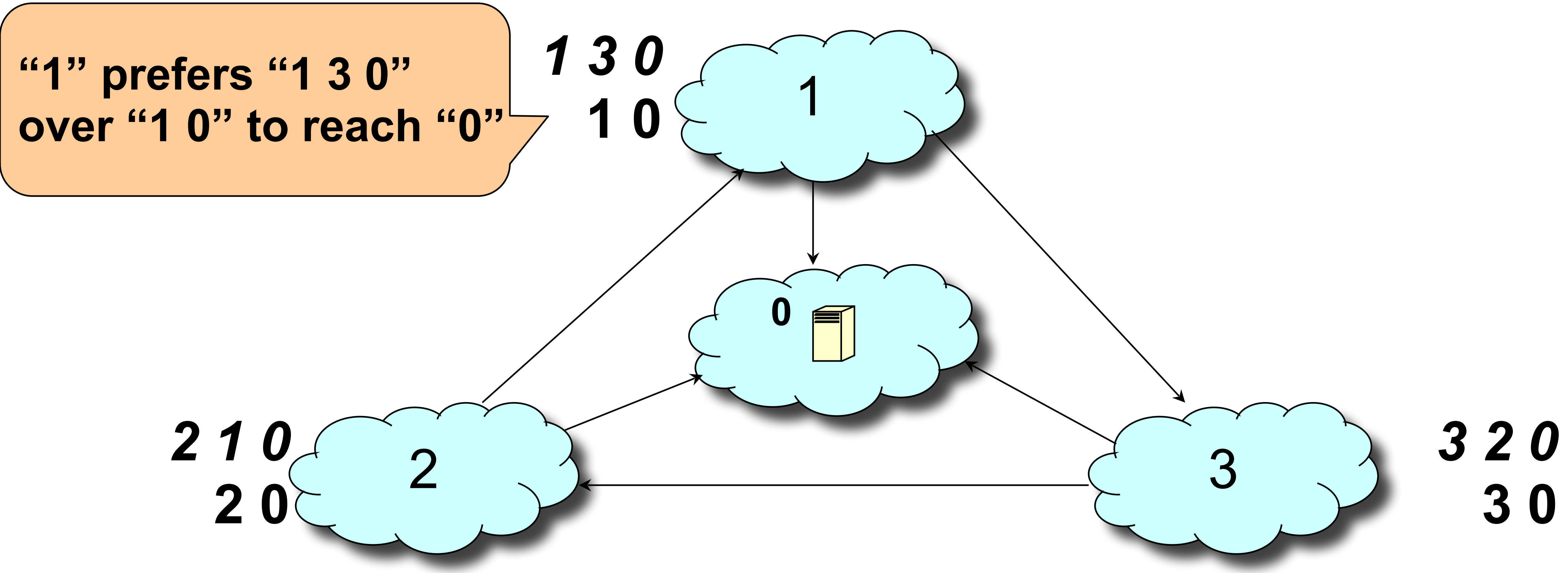
- But…
- AS may forward packets along a route different from what is advertised
  - Tell customers about a fictitious short path…
  - Much harder to fix!

Convergence

- If all AS policies follow Gao-Rexford rules,
  - Then BGP is guaranteed to converge (safety)

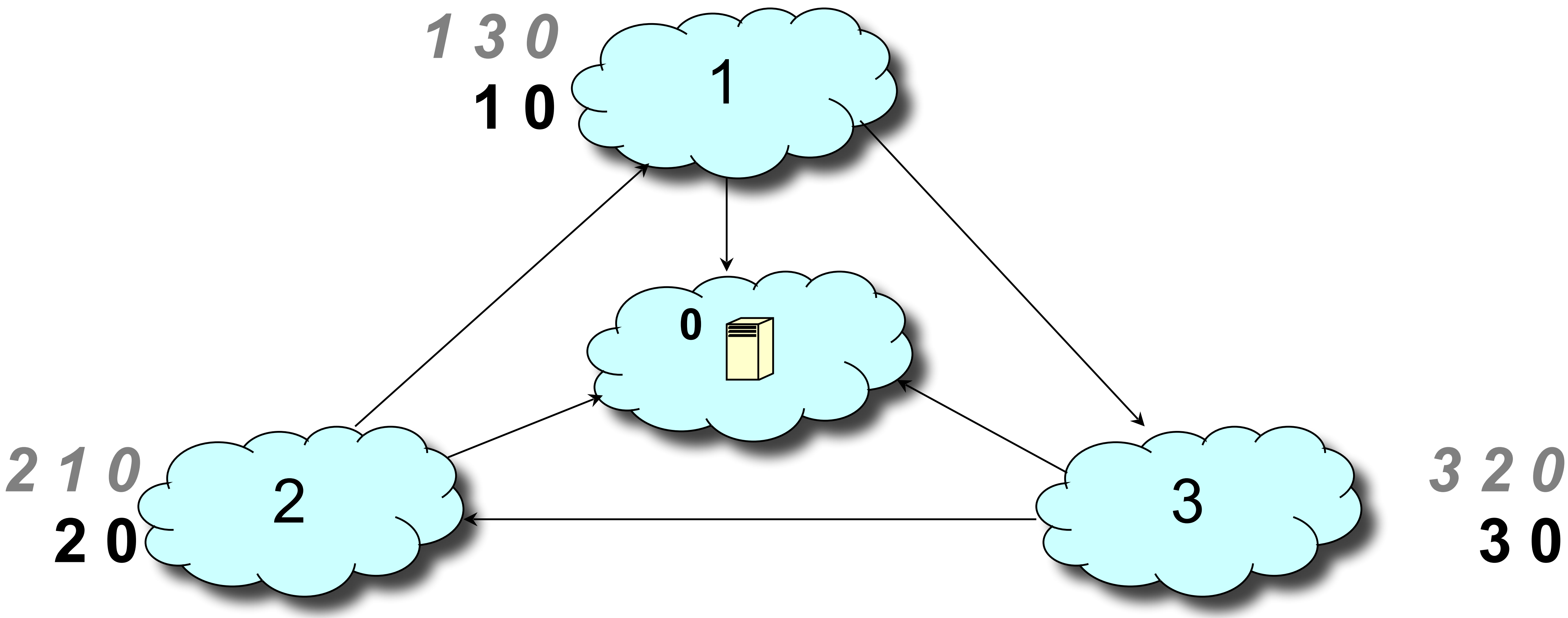
- For arbitrary policies, BGP may fail to converge!

Example of Policy Oscillation



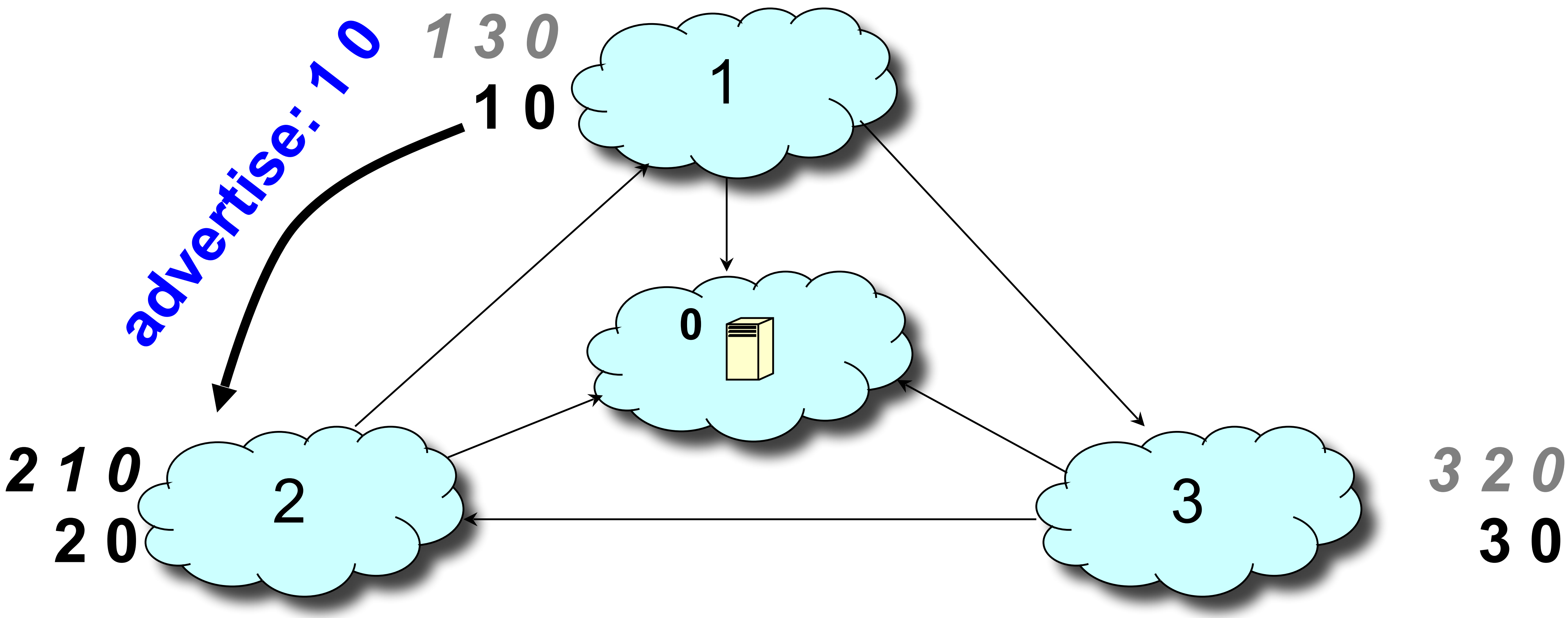
Step-by-step Policy Oscillation

Initially: nodes 1, 2, 3 know only shortest path to 0

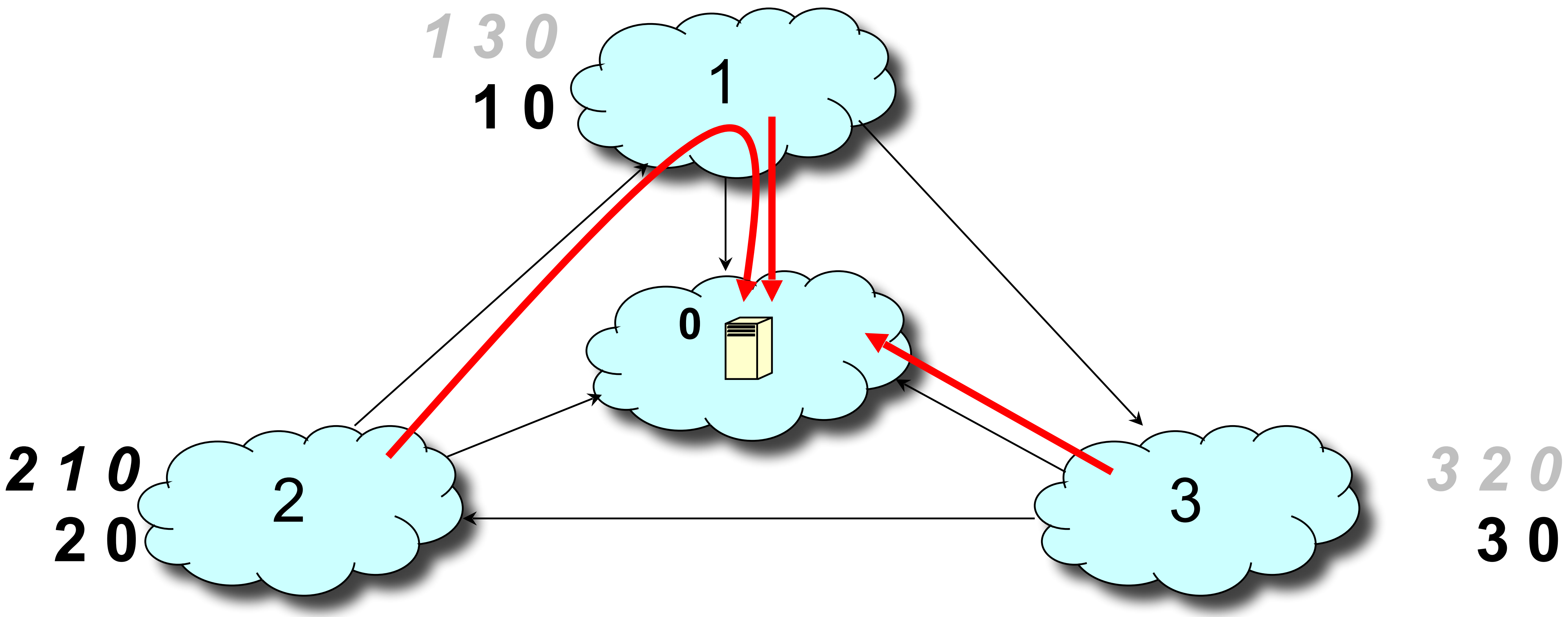


Step-by-step Policy Oscillation

1 **advertises** its path 1 0 to 2

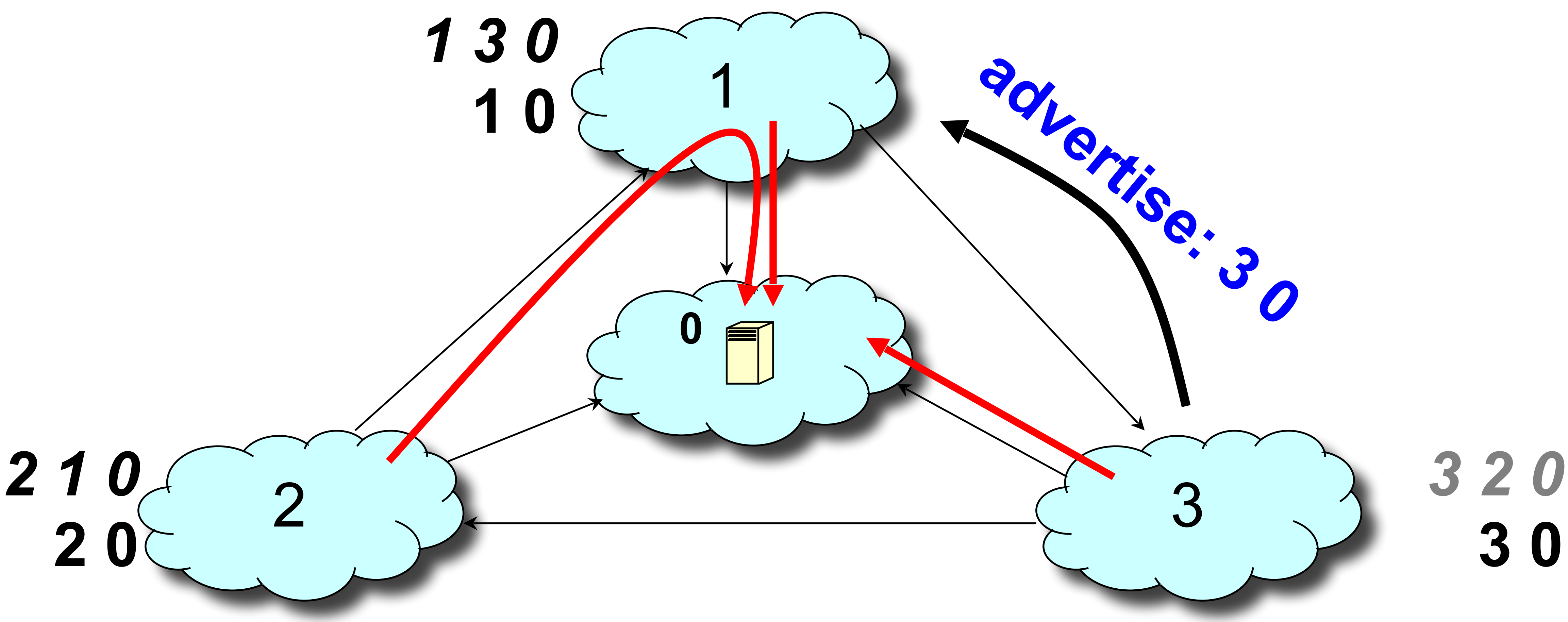


Step-by-step Policy Oscillation

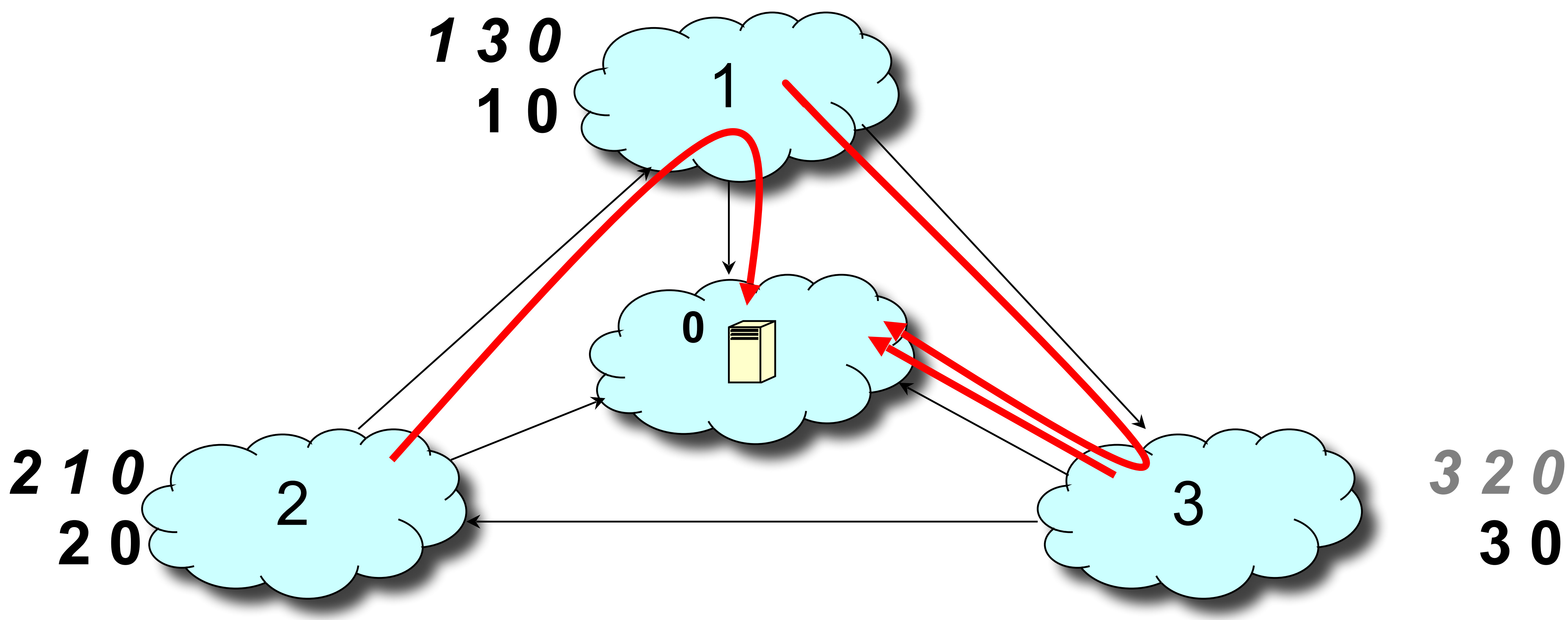


Step-by-step Policy Oscillation

3 **advertises** its path 3 0 to 1

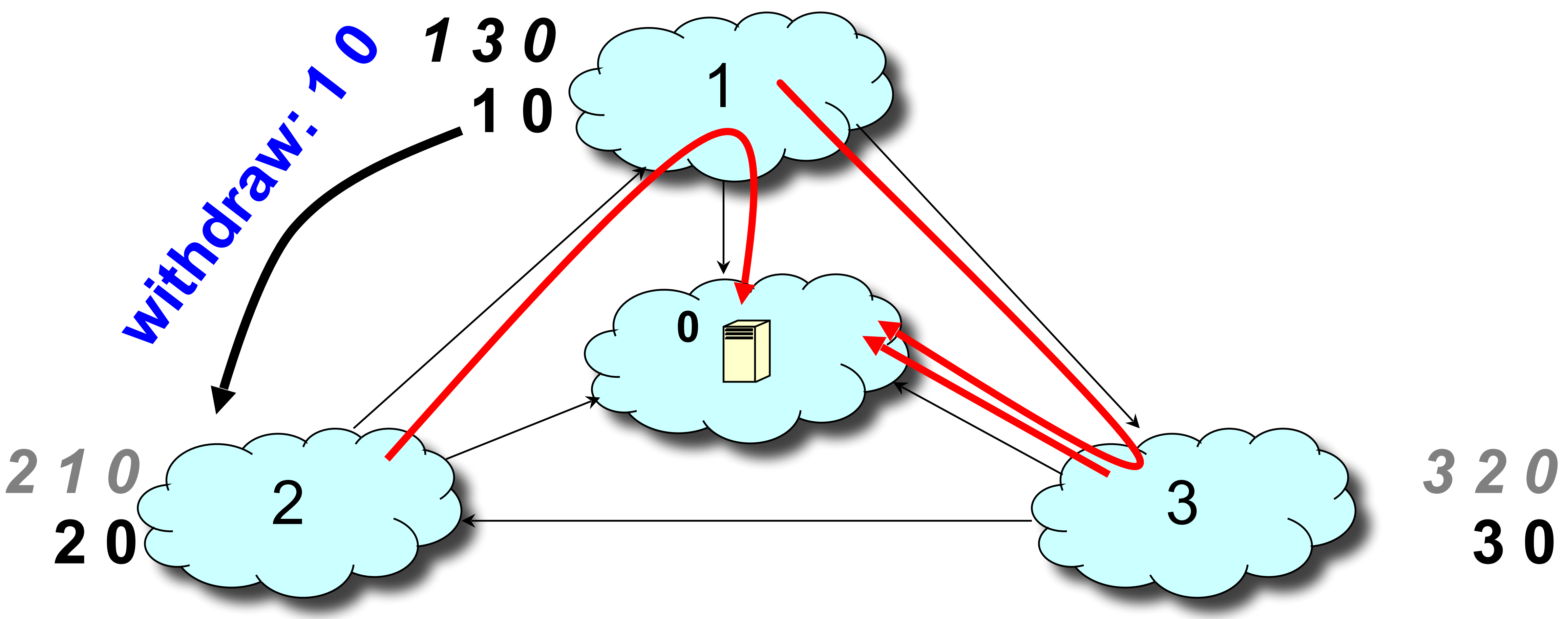


Step-by-step Policy Oscillation

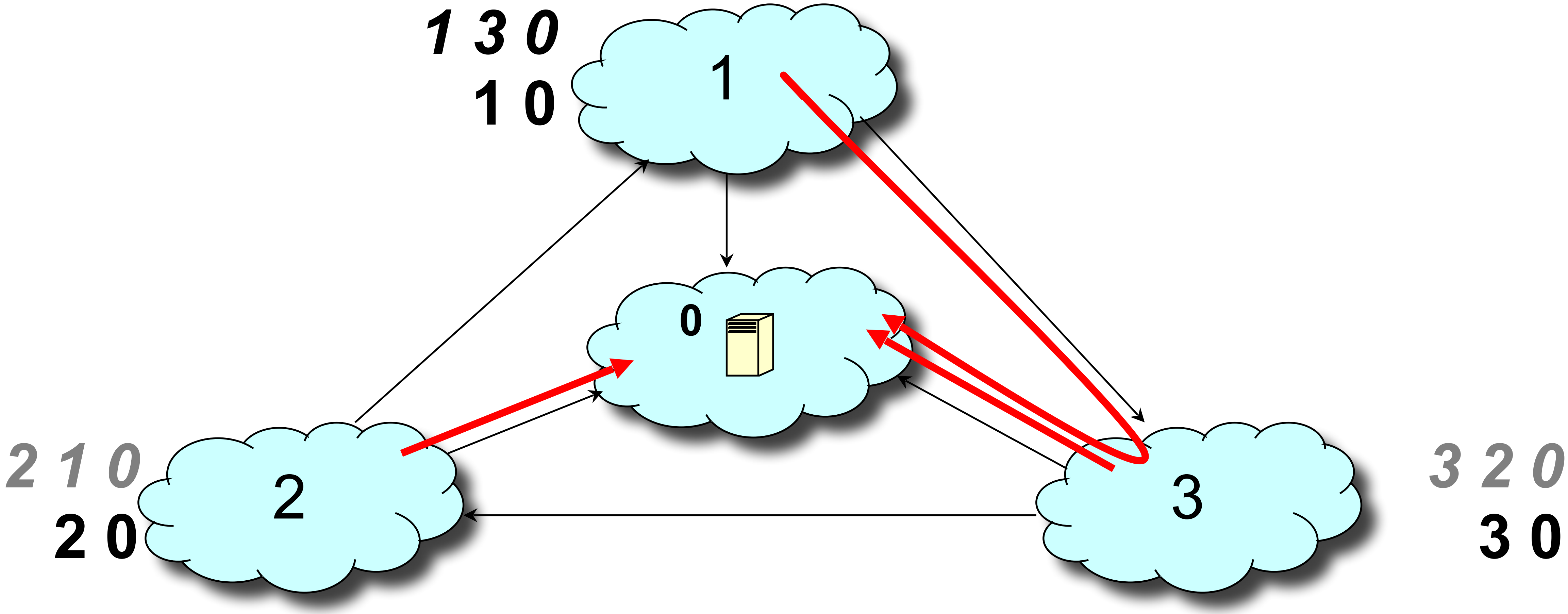


Step-by-step Policy Oscillation

1 **withdraws** its path 1 0 from 2

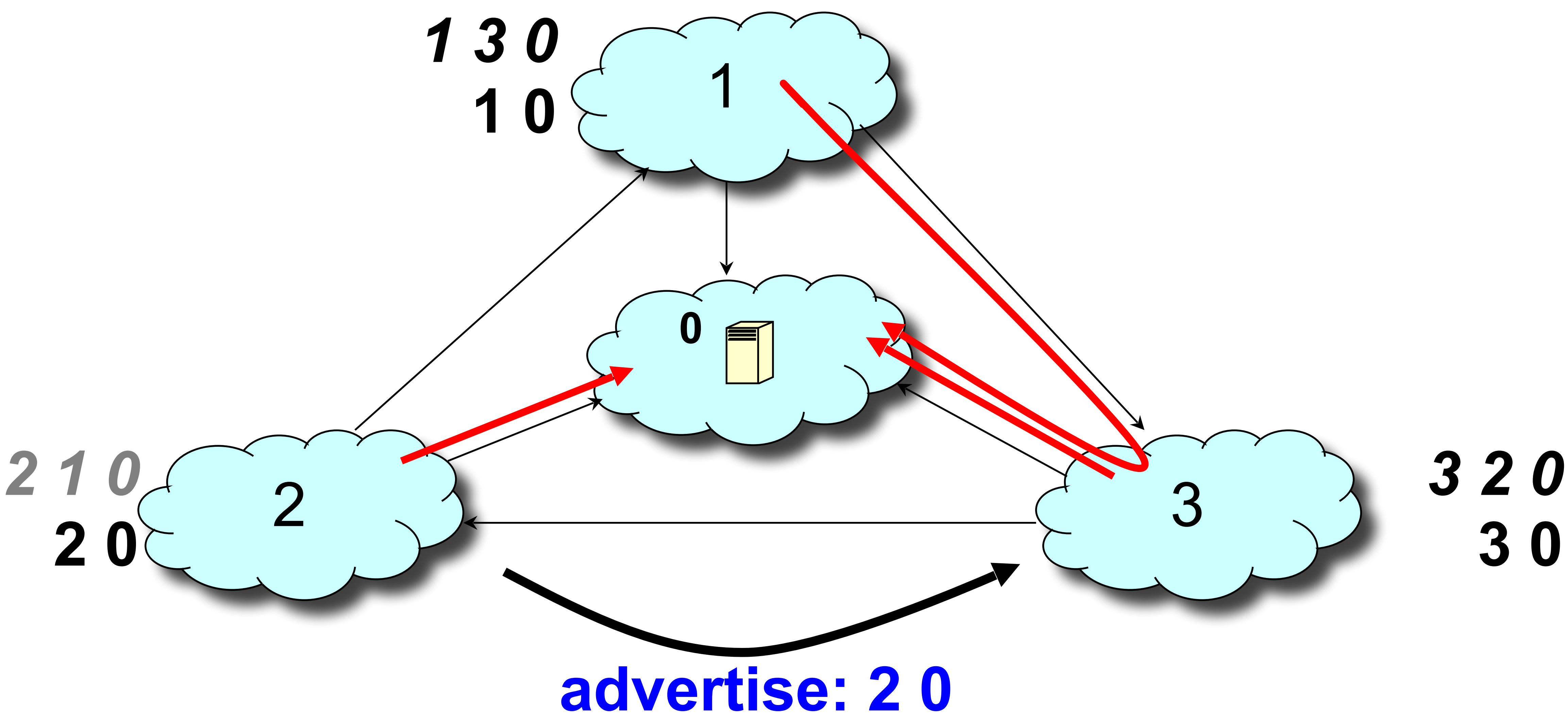


Step-by-step Policy Oscillation

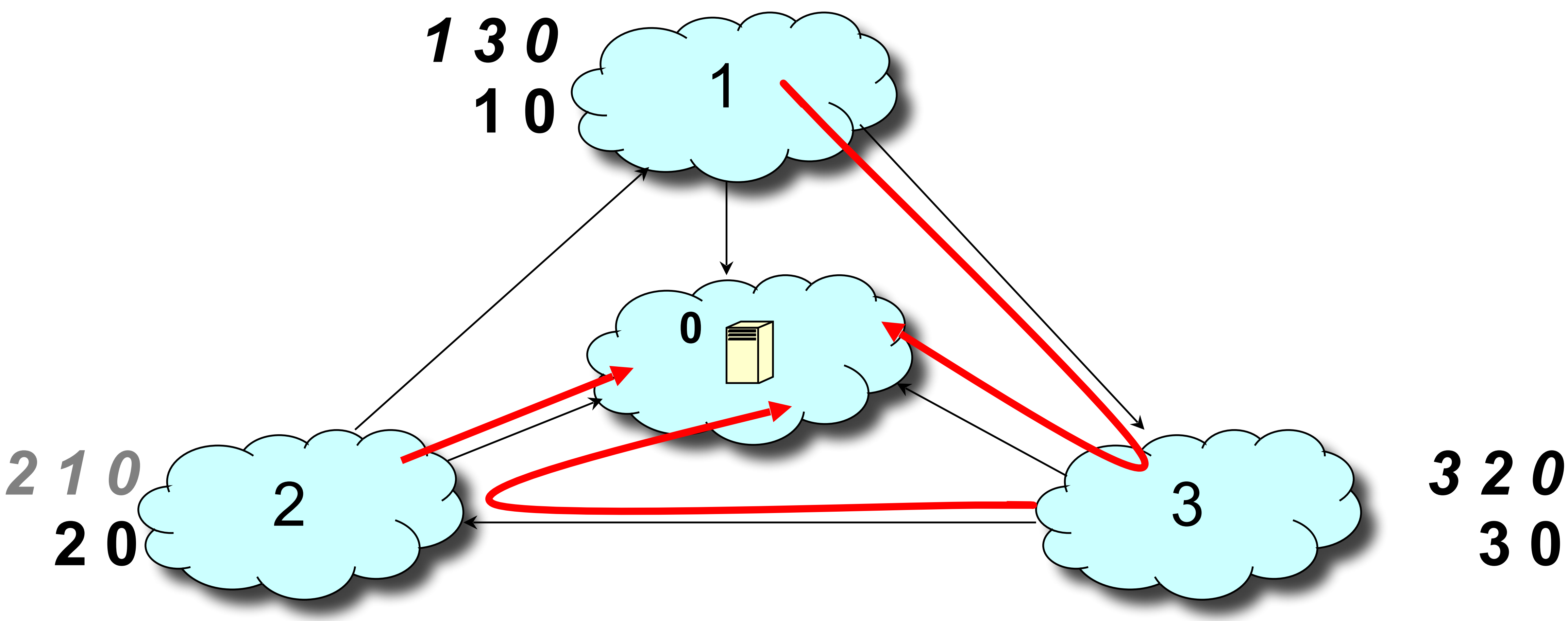


Step-by-step Policy Oscillation

2 **advertises** its path 2 0 to 3

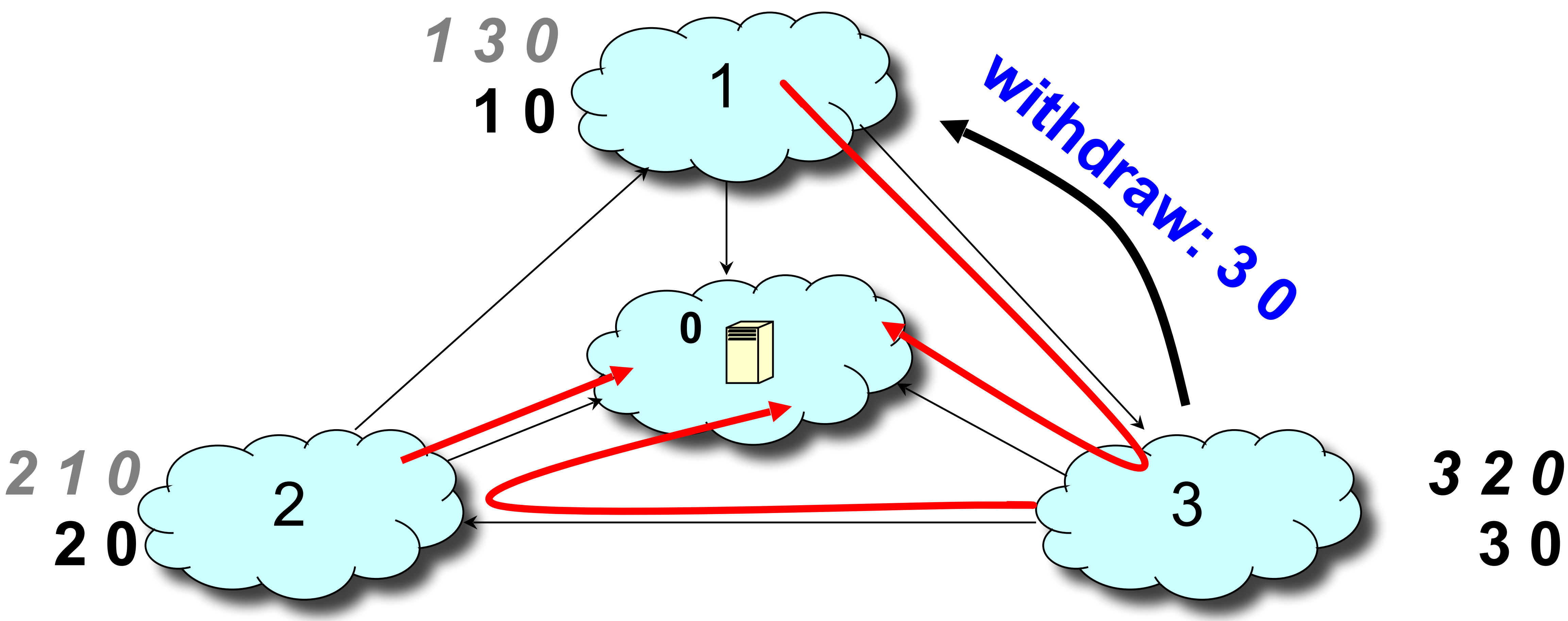


Step-by-step Policy Oscillation

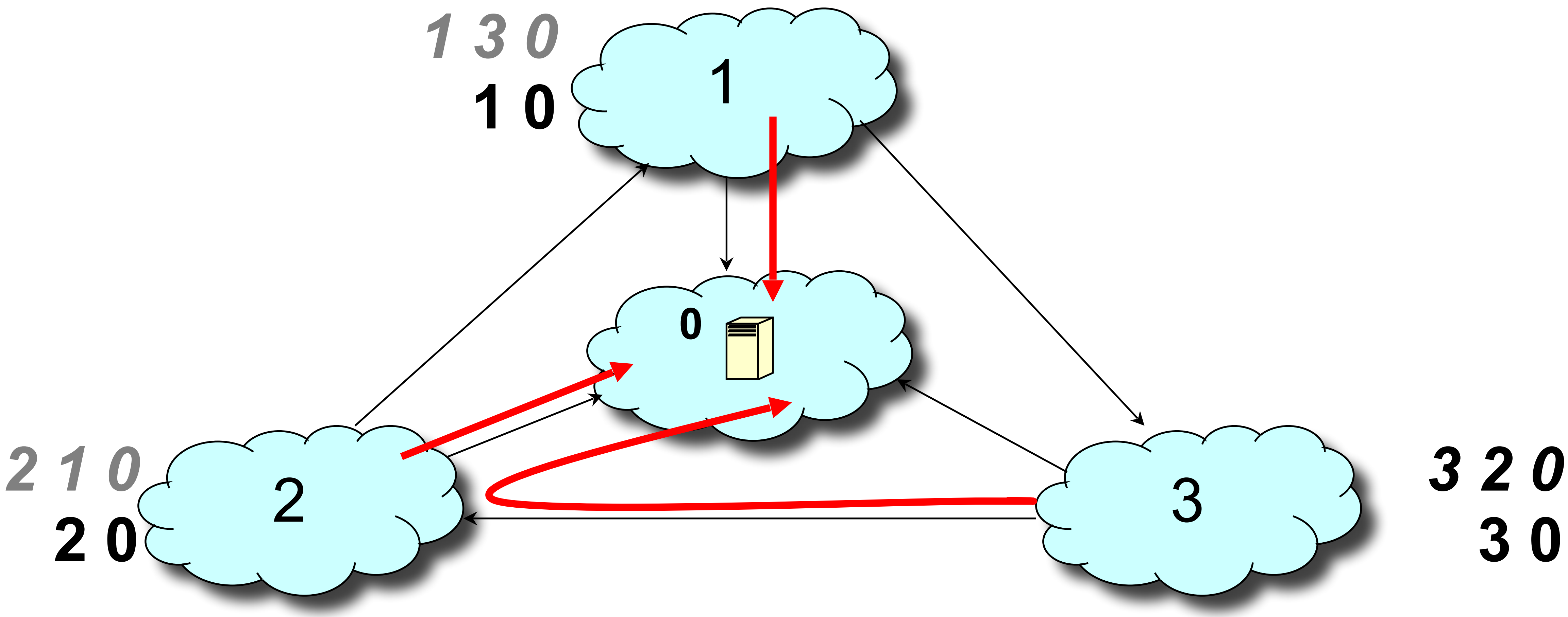


Step-by-step Policy Oscillation

3 **withdraws** its path 3 0 from 1

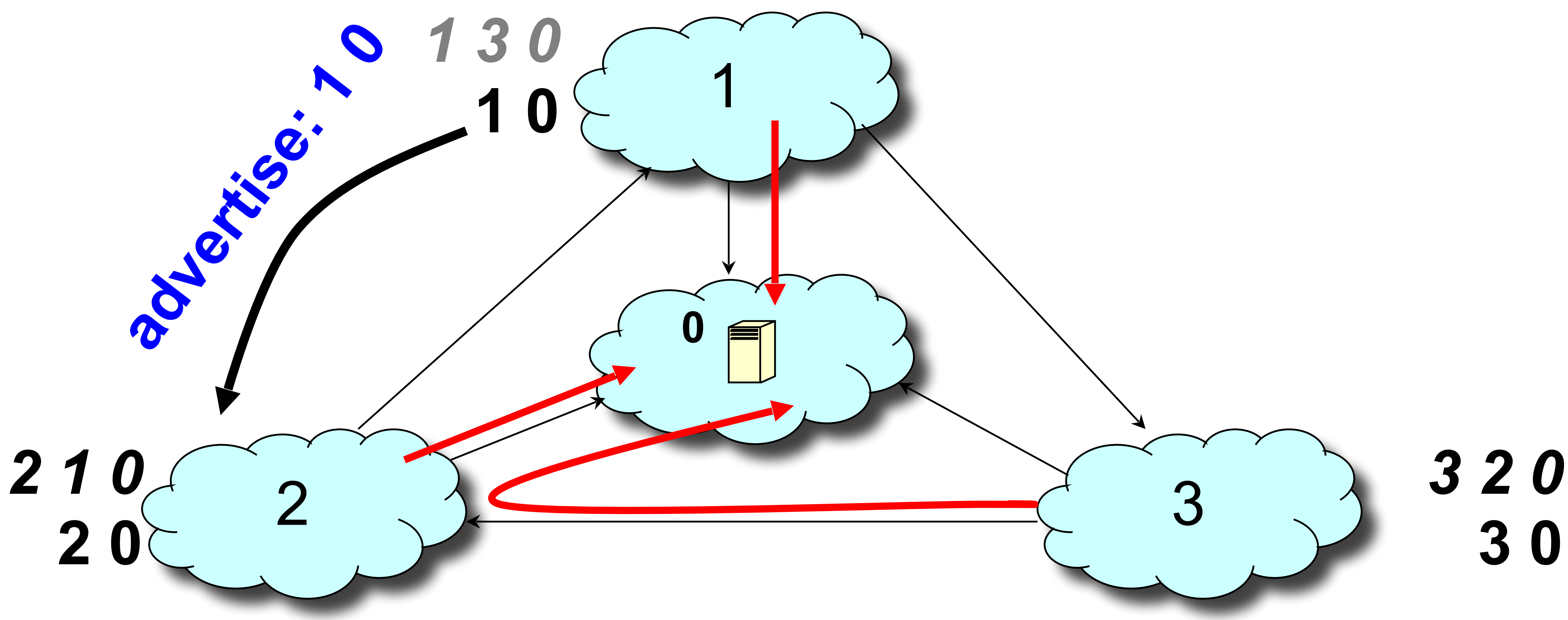


Step-by-step Policy Oscillation

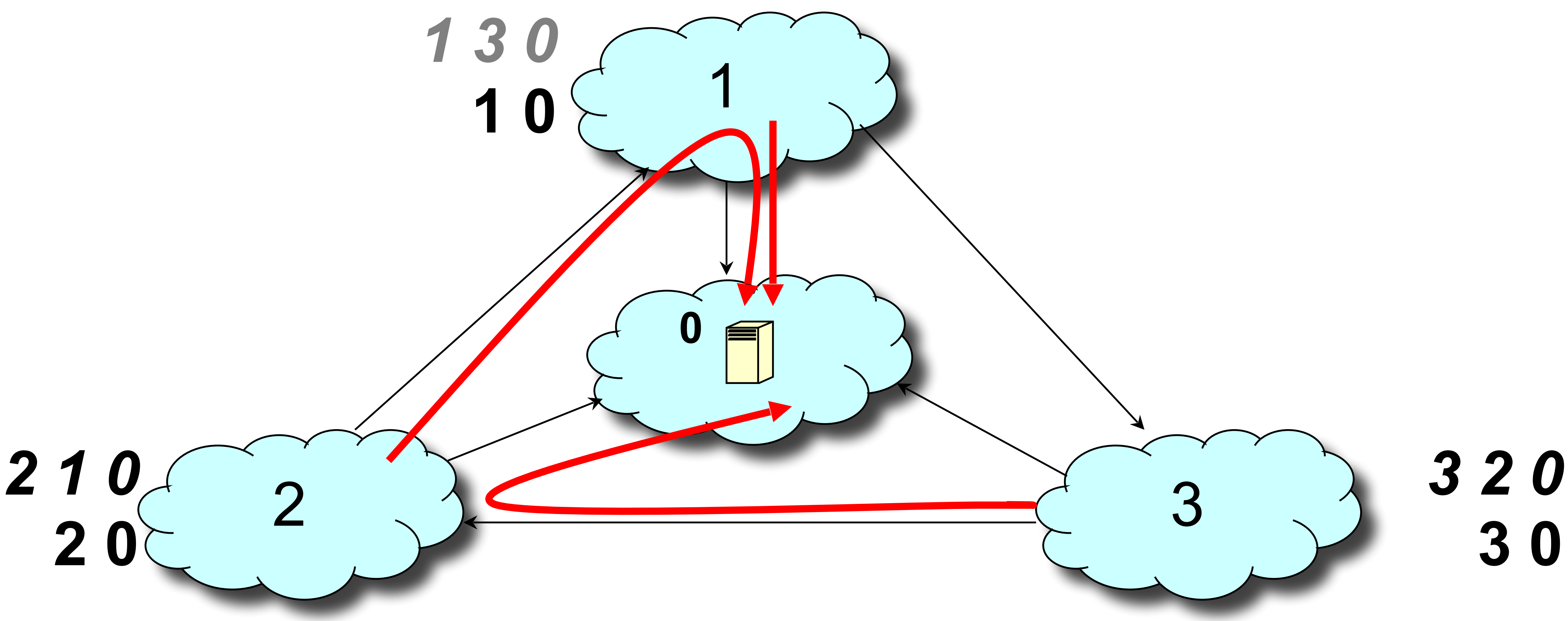


Step-by-step Policy Oscillation

1 **advertises** its path 1 0 to 2

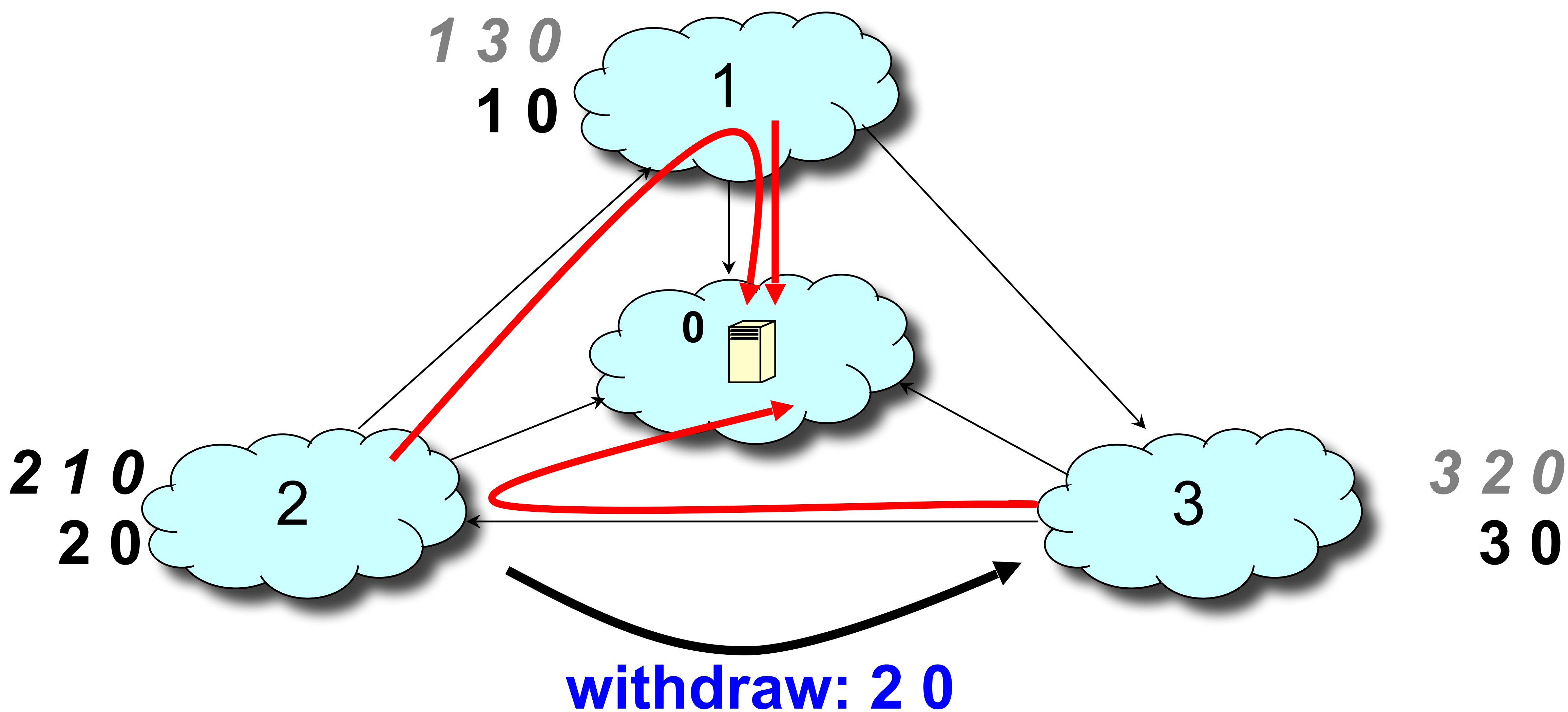


Step-by-step Policy Oscillation

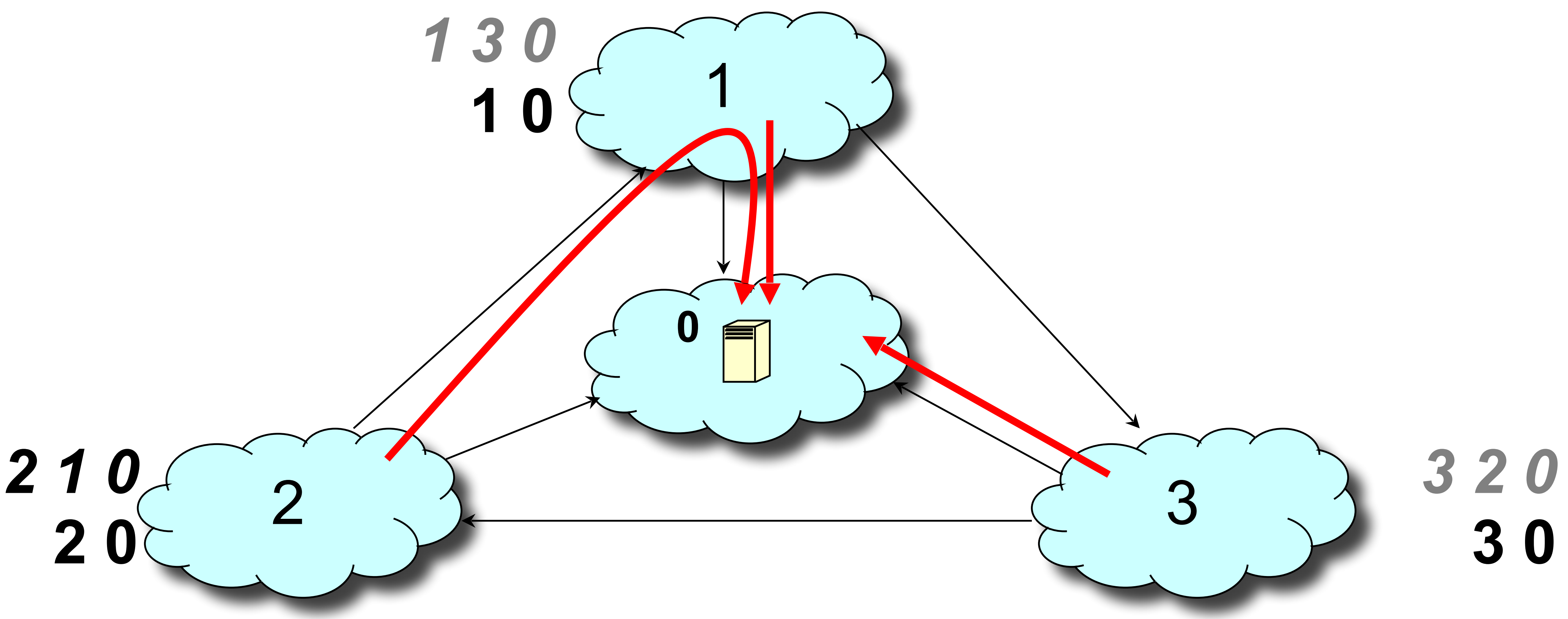


Step-by-step Policy Oscillation

2 **withdraws** its path 2 0 from 3



Step-by-step Policy Oscillation



We are back to where we started!

Convergence

- If all AS policies follow Gao-Rexford rules,
  - Then BGP is guaranteed to converge (safety)

- For arbitrary policies, BGP may fail to converge!

- Why should this trouble us?

Performance Non-Issues

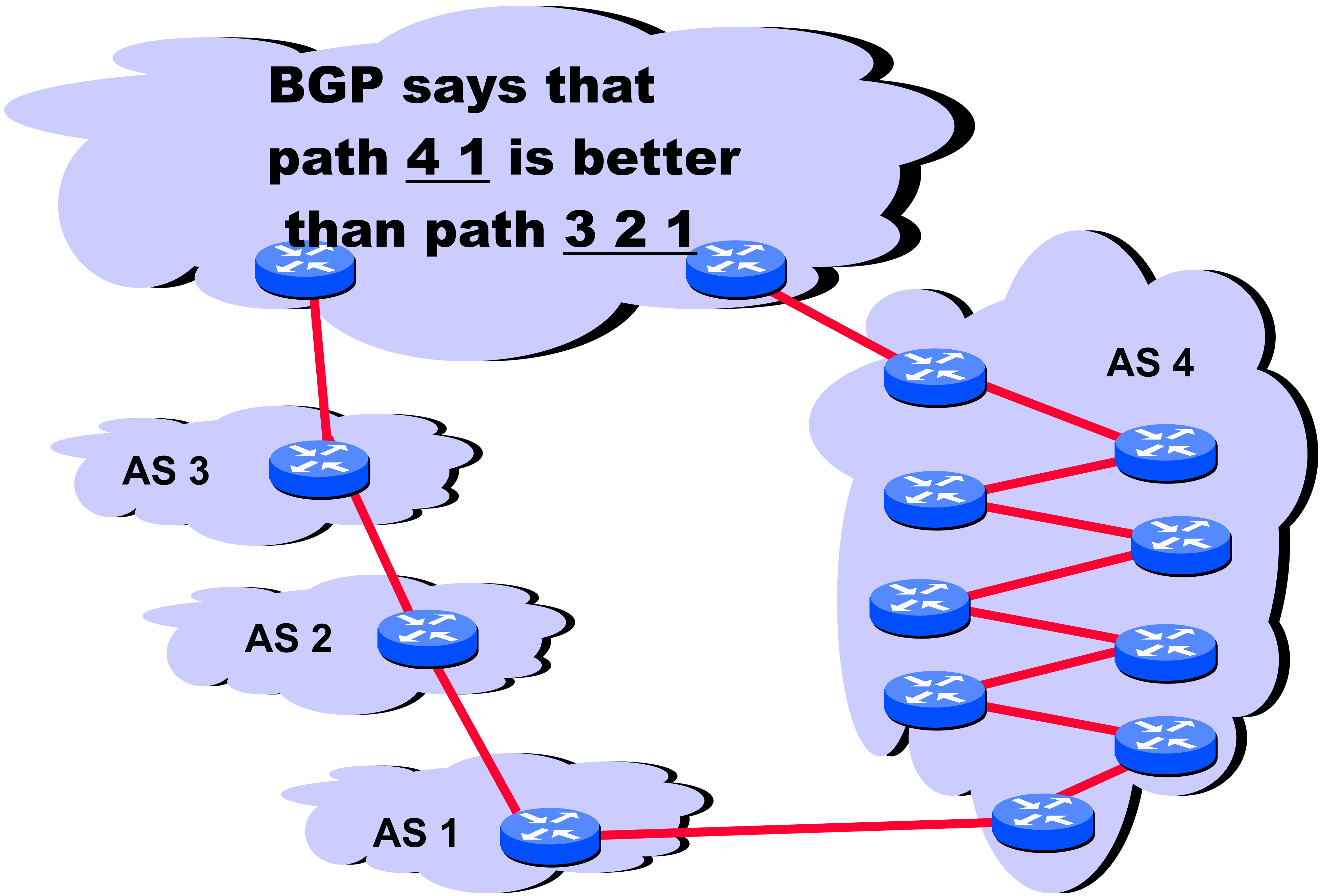
- Internal Routing
  - Domains typically use “hot potato” routing
  - Not always optimal, but economically expedient

- Policy not about performance
  - So policy-chosen paths aren’t shortest

- AS path length can be misleading
  - 20% of paths inflated by at least 5 router hops

Performance (example)

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



Performance: Real Issue

Slow Convergence

- BGP outages are biggest source of Internet problems
- Labovitz et al. *SIGCOMM'97*
  - 10% of routes available less than 95% of the time
  - Less than 35% of routes available 99.99% of the time
- Labovitz et al. *SIGCOMM 2000*
  - 40% of path outages take 30+ minutes to repair
- But most popular paths are very stable

BGP Misconfigurations

- BGP protocol is both bloated and underspecified
  - Lots of attributes
  - Lots of leeway in how to set and interpret attributes
  - Necessary to allow autonomy, diverse policies
  - … But also gives operators plenty of rope

- Much of this configuration is manual and *ad hoc*

- And the core abstraction is fundamentally flawed
  - Disjoint per-router configuration to effect AS-wide policy
  - Now strong industry interest in changing this!

BGP: How did we get here?

- BGP was designed for a different time
  - Before commercial ISPs and their needs
  - Before address aggregation
  - Before multi-homing

- **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)**

- We don’t get a second chance: ‘clean slate’ designs virtually impossible to deplay
- Thought experiment: how would you design a policy-driven interdomain routing solution?
  - How would you deploy it?