CS4450

Computer Networks:
Architecture and Protocols

Lecture 14
IP: Addressing and Forwarding

Spring 2018
Rachit Agarwal

Announcements

- **Please fill out the feedback form**
    - I emailed a link
- **I received your emails regarding conflicts with prelims/final**
    - We'll discuss and respond to emails soon

Goals for Today's Lecture

- **Continue with design of THE Internet Protocol (IP)**

- To achieve its functionality, IP protocol has **three** responsibilities
    - **Addressing hosts**
    - **Forwarding packets (actually datagrams)**

Addressing

Addressing so far

- Each node has a "name"
    - We have so far worked only with names
    - Assumed that forwarding/routing etc. done on names
- Today:
    - Why do we need addresses?
    - Why do we assign addresses the way we assign addresses?

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**

Layer 2 (link layer): “Flat” Addressing

- Uses MAC address
  - “Names”, remember? Used as identifier
- Unique identifiers hardcoded in the hardware
  - No location information
- Local area networks route on these “flat” addresses
  - **Spanning Tree Protocol runs on switches and hosts**
  - Each switch stores a separate routing entry **for each host**
  - End-hosts store nothing
- Upon receiving a packet, an end-host:
  - Puts destination’s and its own MAC address in the header
  - Forwards it to the switch it is connected to
- **Destination is able to recognize the packet is for them using address**

How does this meet our requirements?

- **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

Conclusion: L2 addressing does not enable scalable routing

How would you scale L2?

- Suppose we want to design a much larger L2 network

- Must use MAC address as part of the address
  - Only way host knows that the packet is for them

- **But how would you enable scalable routing?**
  - Small #routing entries (less than one entry per host per switch)
  - Small #updates (less than one update per switch per host change)

One possible Solution: Towards Internet-scale addressing

- Assign each end-host an addresses of the form — Switch:MAC

- Spanning Tree Protocol runs only on switches
  - So, each switch has one entry per switch (rather than per host)

- Upon receiving a packet, an end-host:
  - Puts destination's and its own Switch:MAC address in the header
  - Forwards it to the switch it is connected to

- **Switches forward the packet using first part of the address**

- **Destination is able to recognize the packet is for them using second part of the address**

Layer 3 (IP): 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
- **This was the original IP addressing scheme**

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

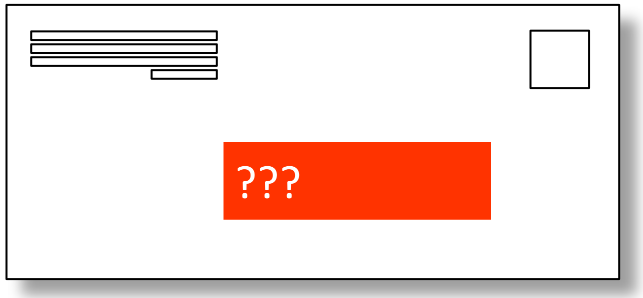
- The Internet is an “inter-network”
  - Used to connect networks together, not hosts

- 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

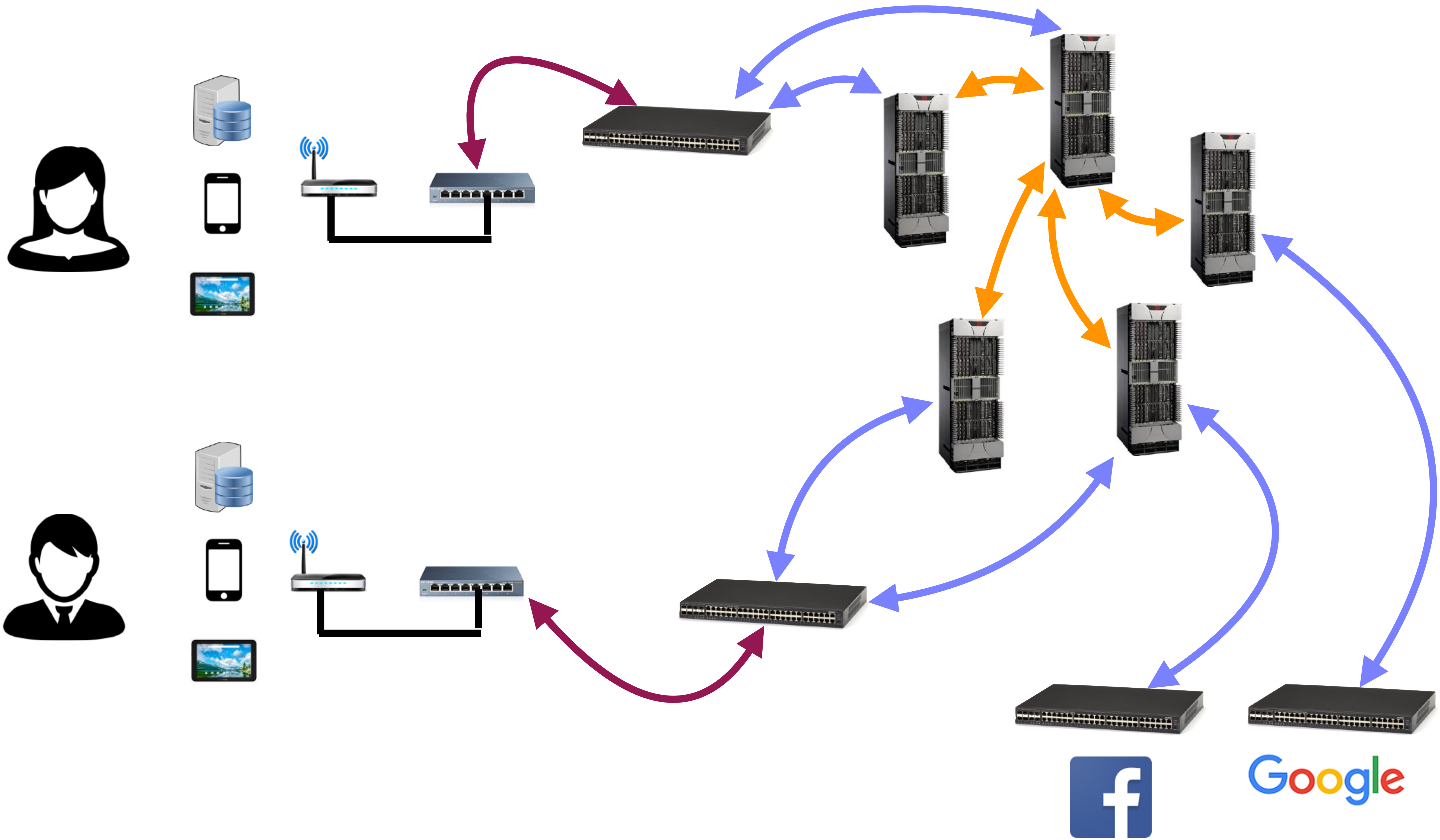
- ICANN gives ARIN several /8s
- ARIN given AT&T one /8, **128.0/8**
  - **Network prefix: 10000000**
- AT&T gives Cornell one /16, **128.84/16**
  - **Network prefix: 10000000 01010100**
- Cornell gives CS one /24, **128.84.139/24**
  - **Network prefix: 10000000 01010100 10001011**
- CS given me a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

How does this meet our requirements?

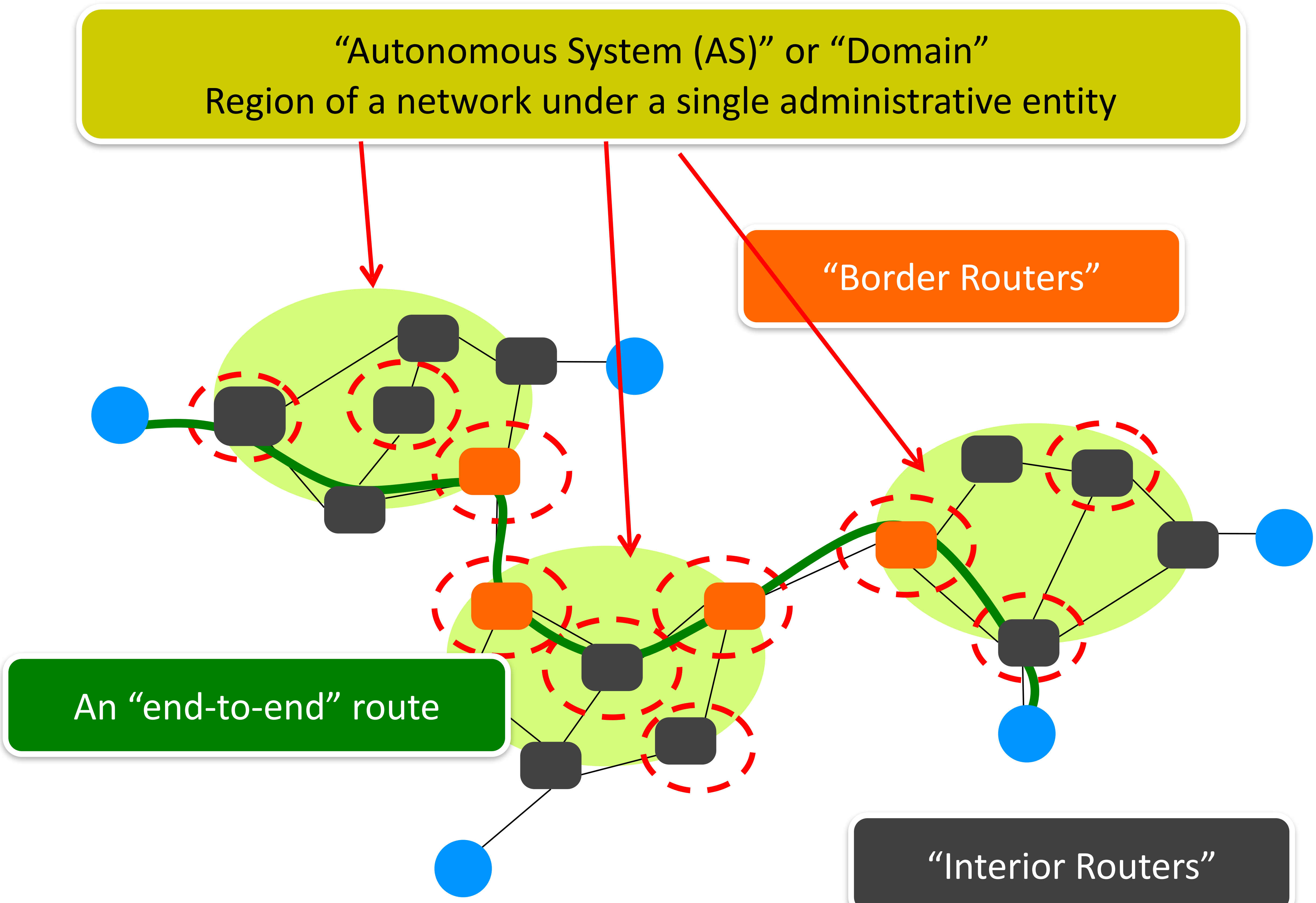
- To understand this, we need to understand the routing on the Internet
- And to understand that, we need to understand the Internet

Back to the basics: what is a computer network?

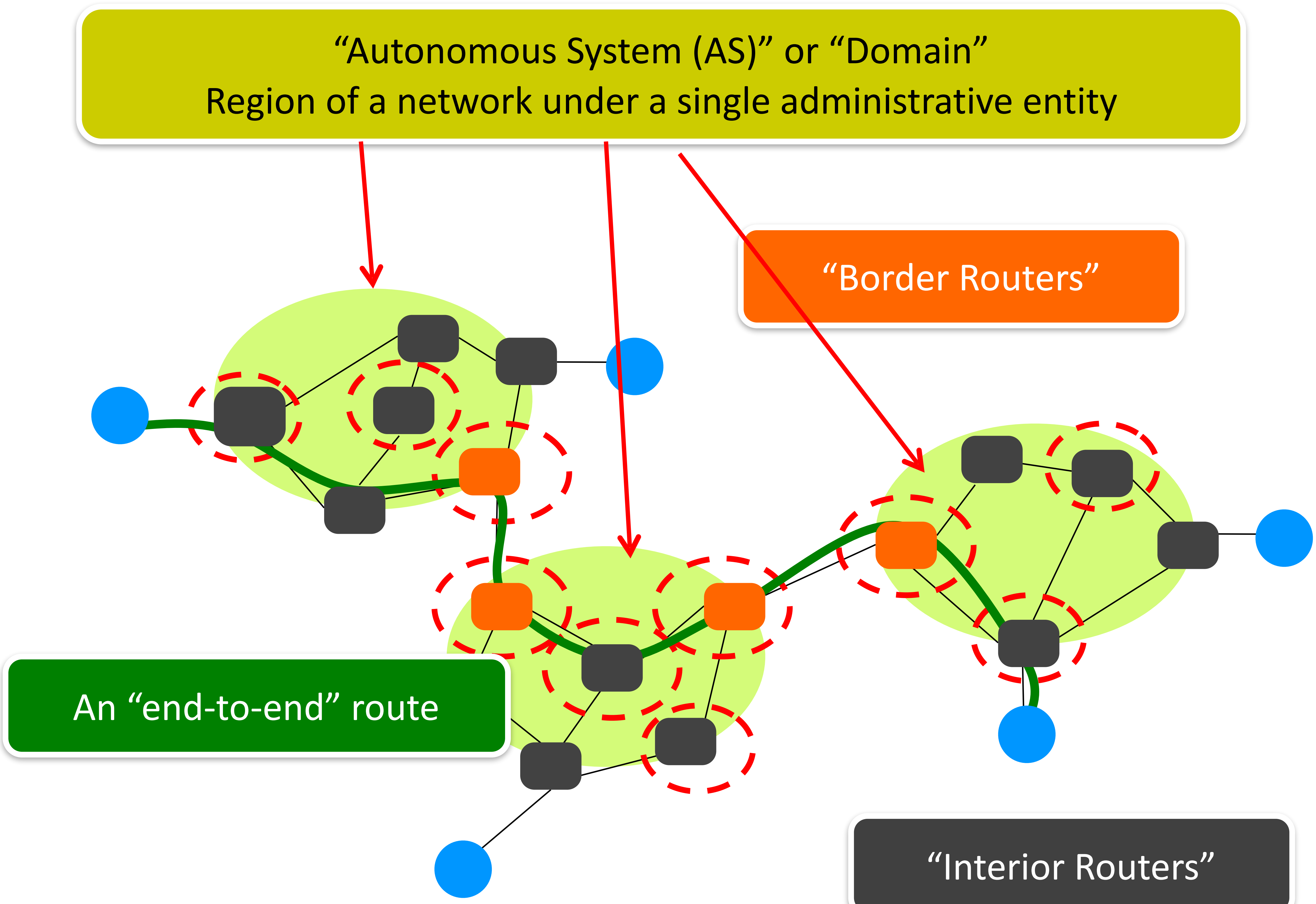
A set of network elements connected together, that implement a set of protocols for the purpose of sharing resources at the end hosts



What does a computer network look like?



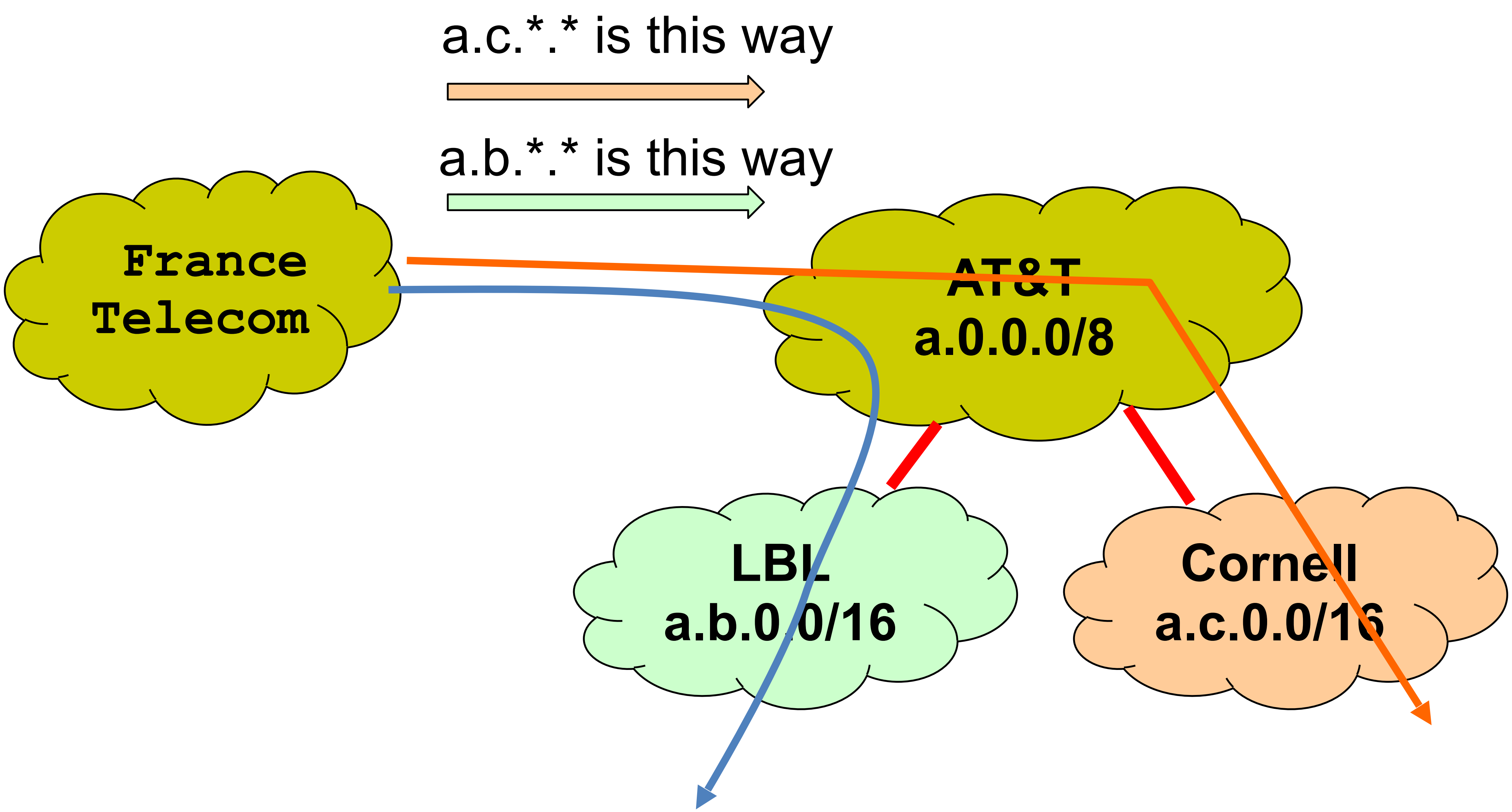
What does a computer network look like?



Autonomous Systems (AS)

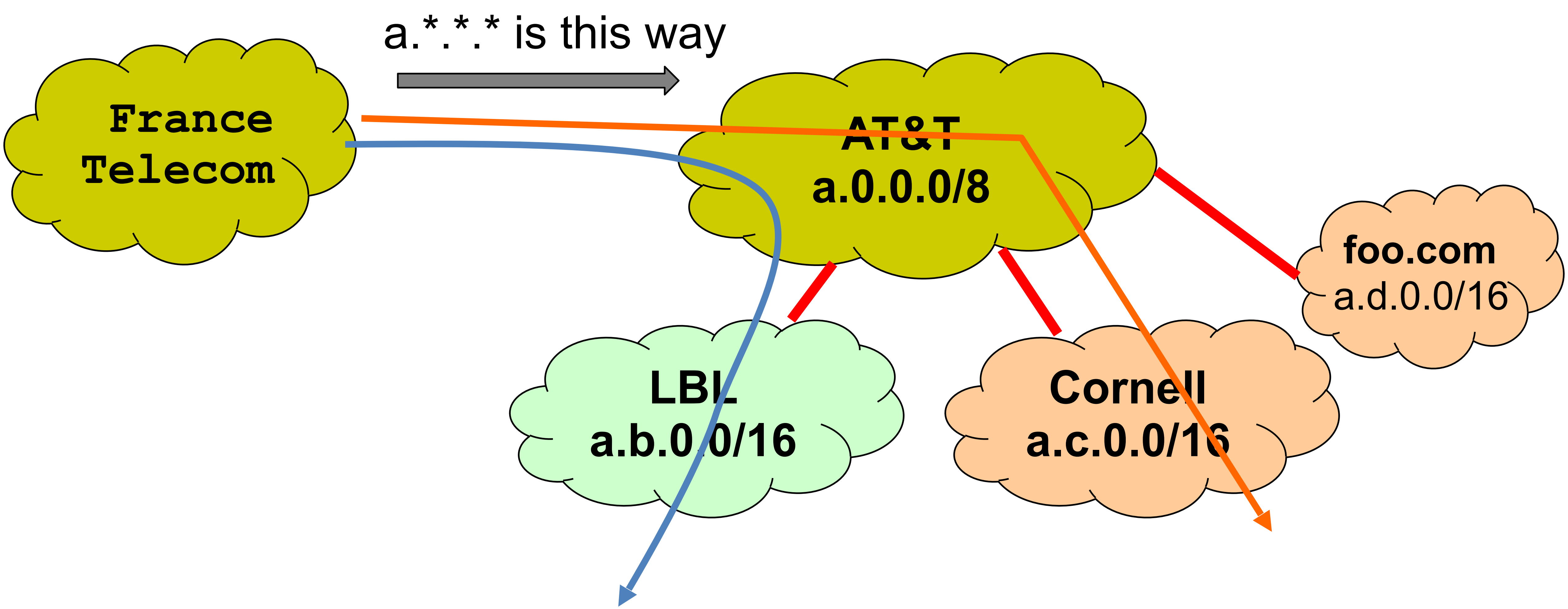
- An AS is a network under a single administrative control
    - Currently over 30,000
    - **Example: AT&T, France Telecom, Cornell, IBM, etc.**
    - A collection of routers interconnecting multiple switched Ethernets
    - And interconnections to neighboring ASes
- Sometimes called “Domains”
- Each AS assigned a unique identifier
    - **16 bit AS number**

IP addressing → Scalable Routing?



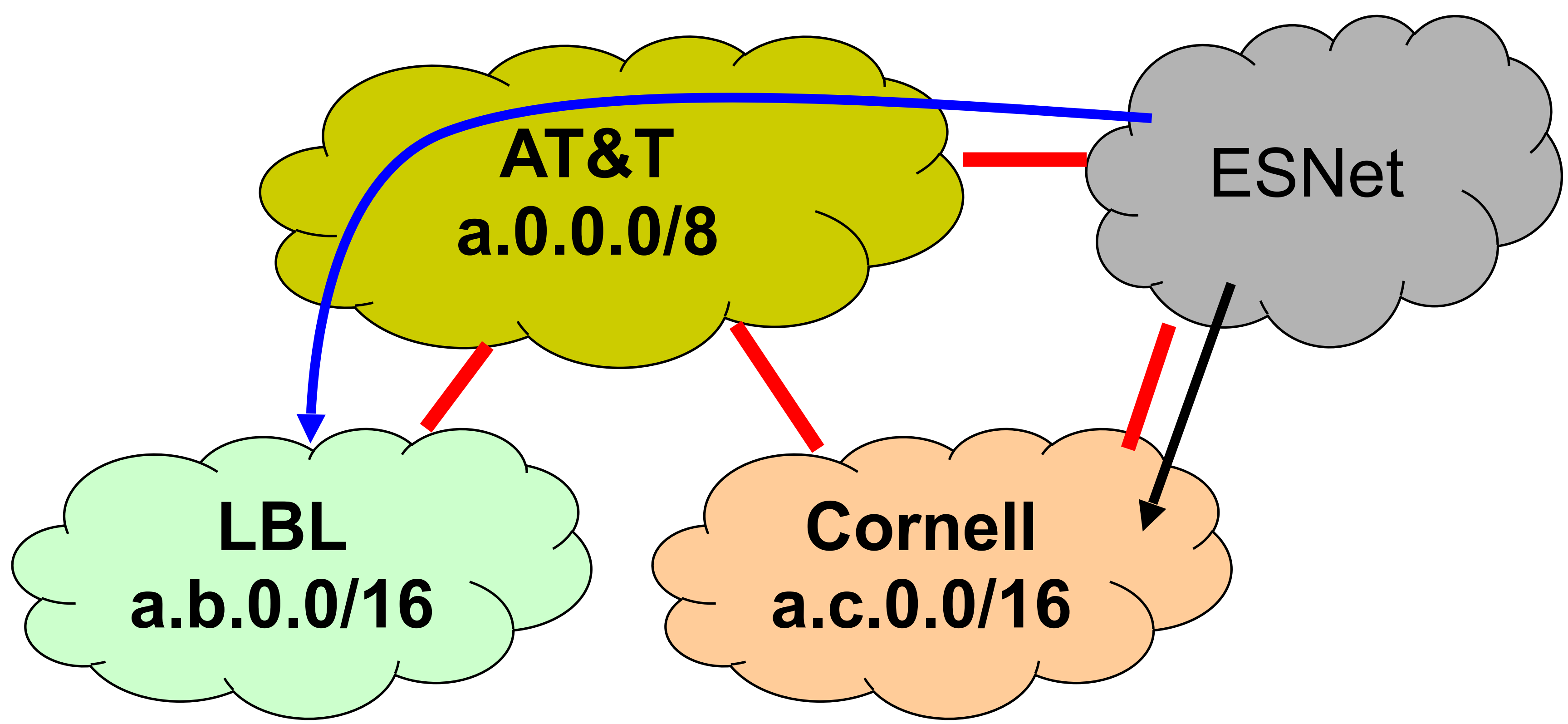
IP addressing → Scalable Routing?

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 Interdomain 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

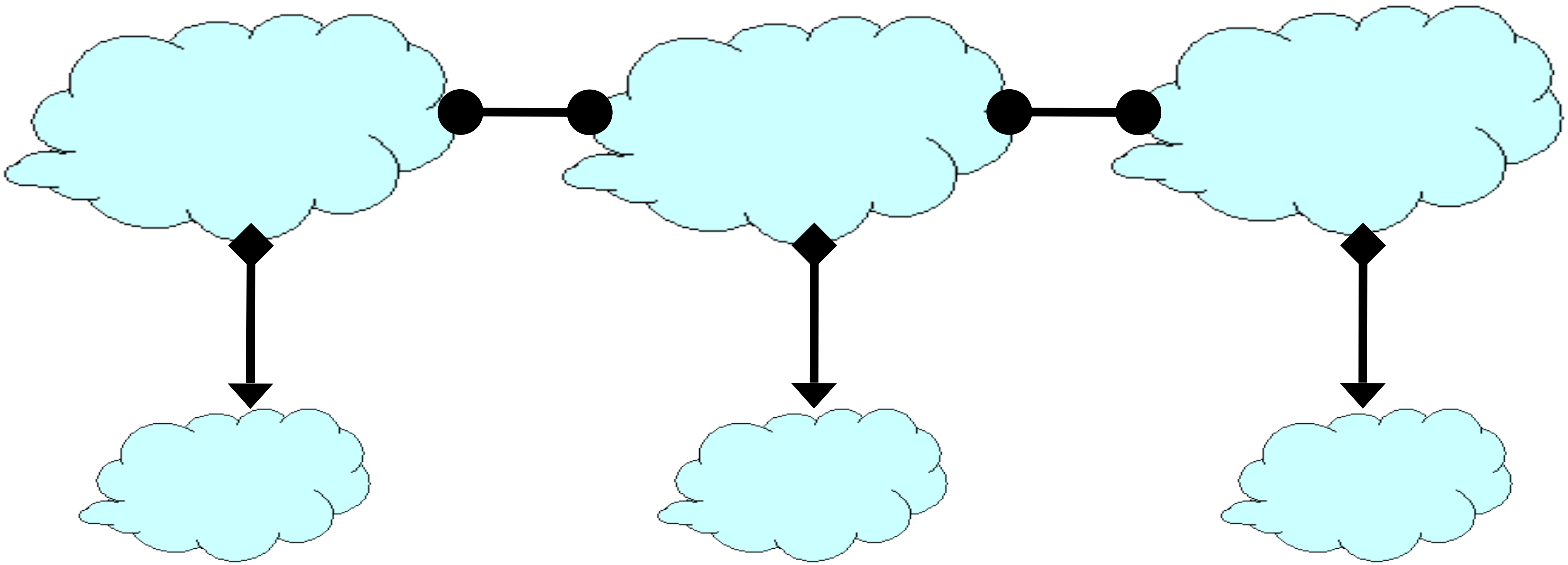
The "Border Gateway Protocol" (BGP) extends Distance-Vector ideas to accomodate policy

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

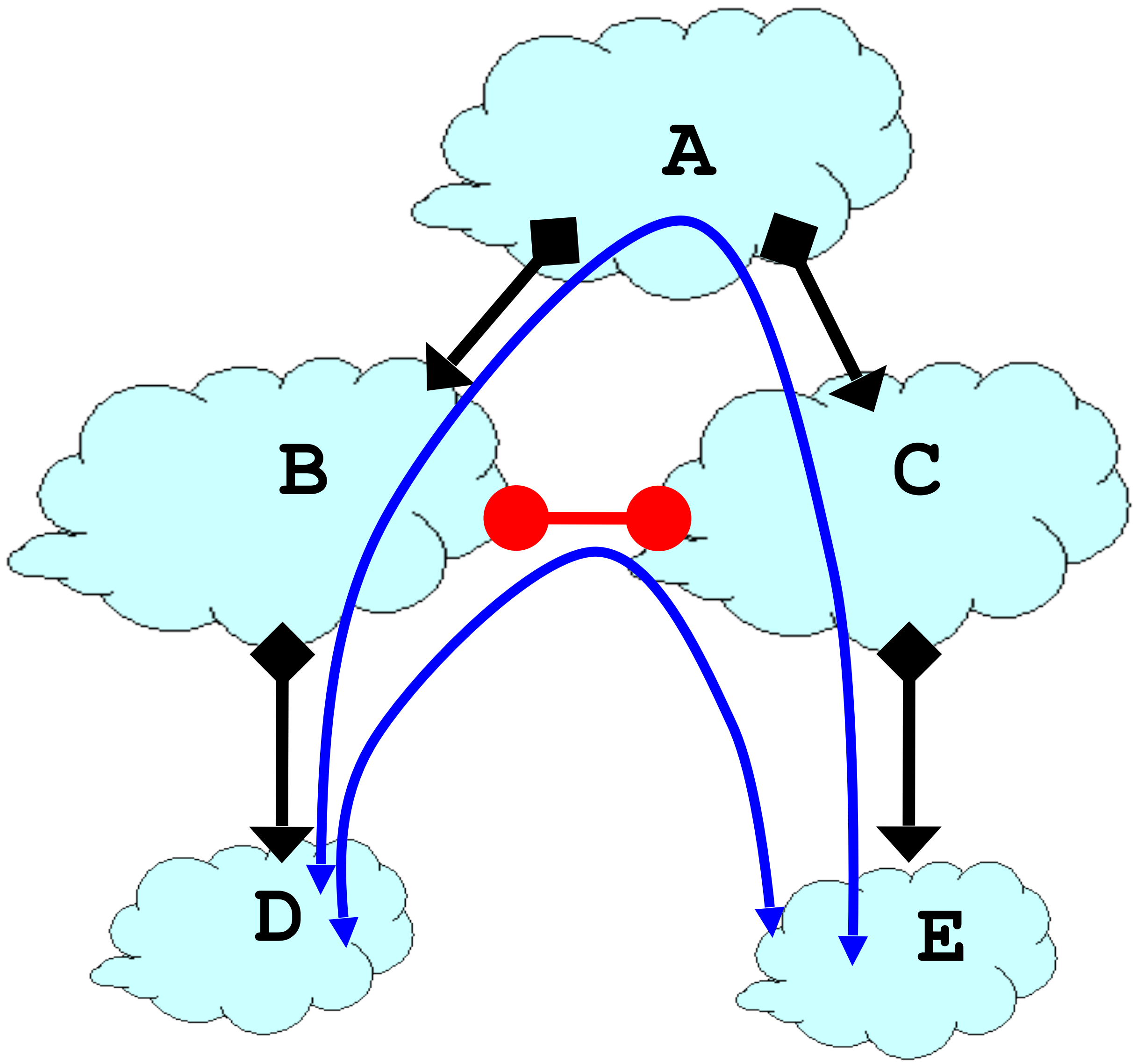
provider ◆——▶ customer

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

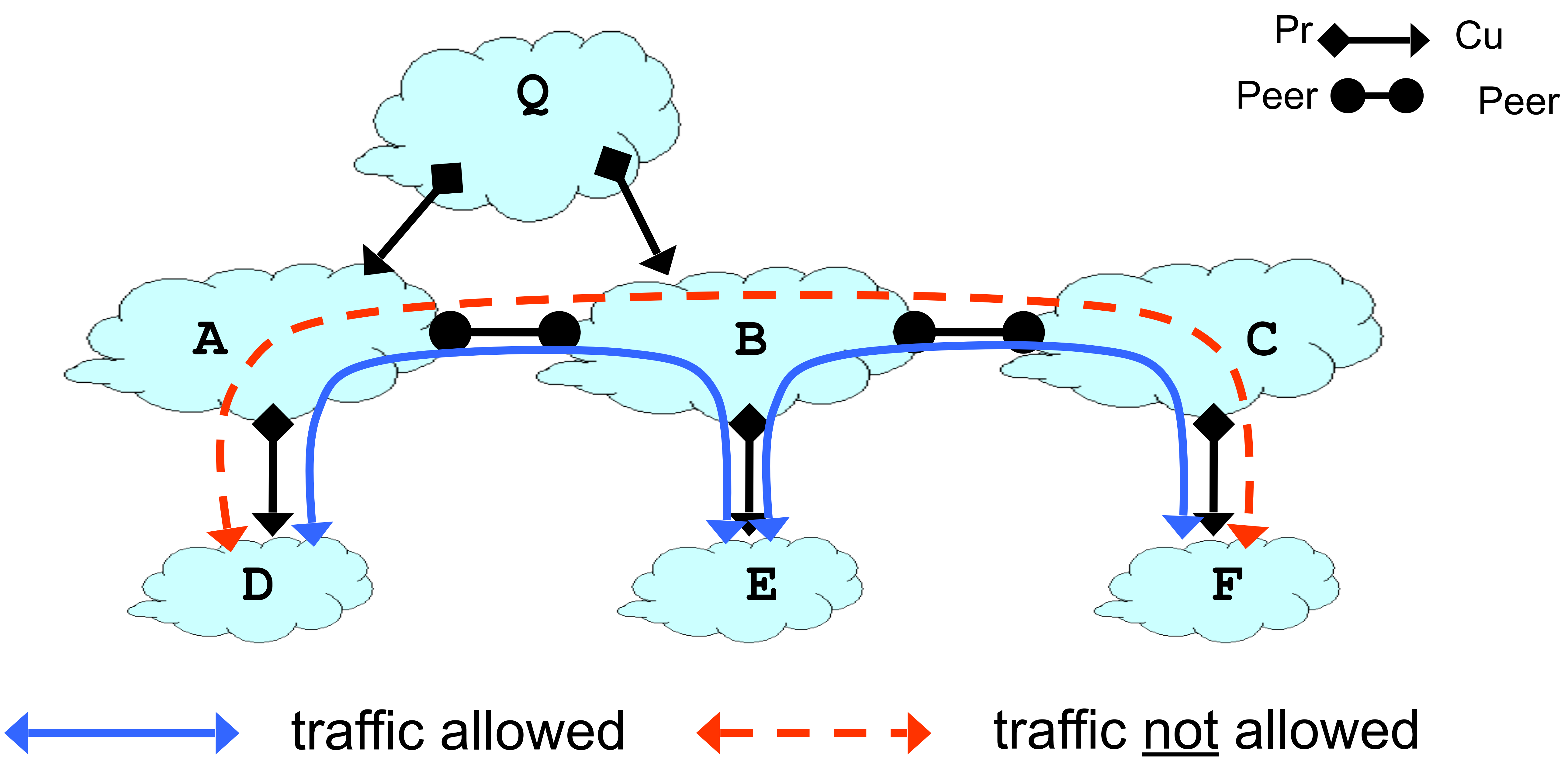
provider ◆——▶ customer

peer ●——● peer

Business Implications

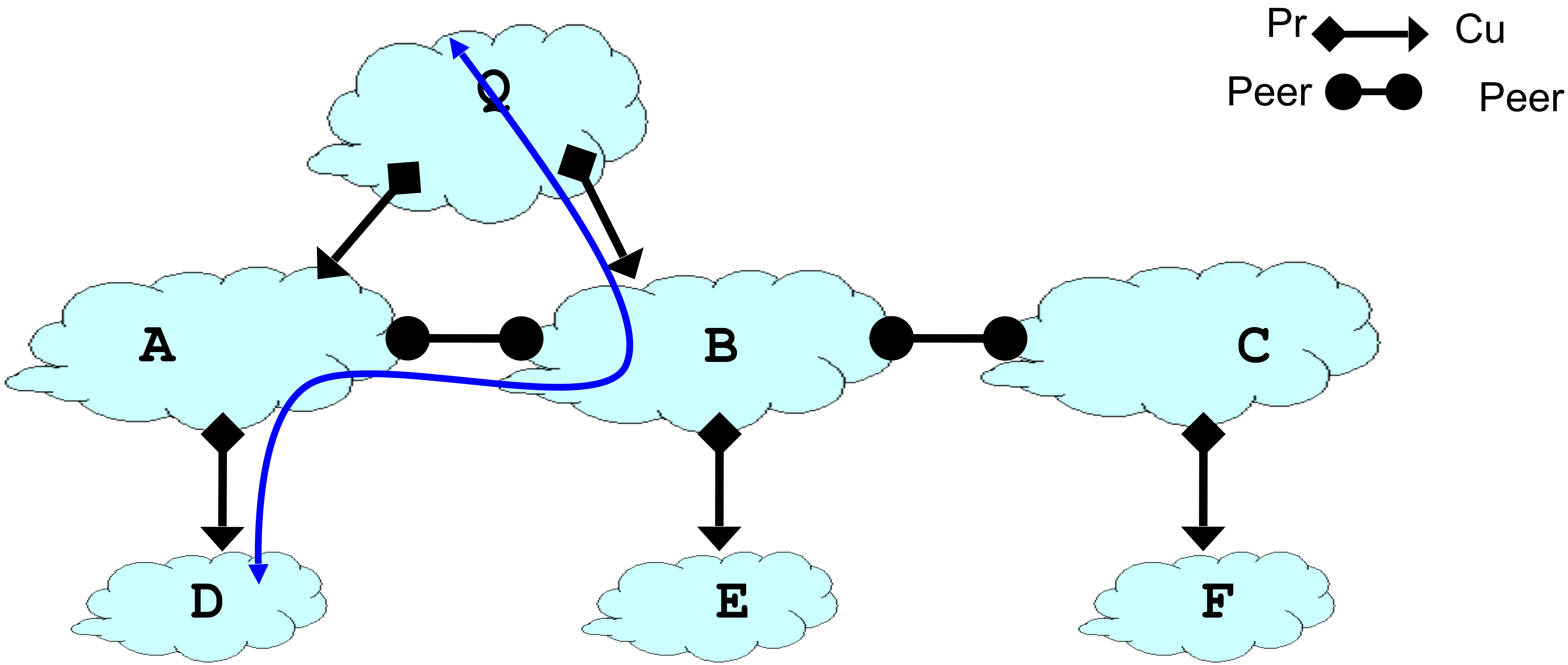
- **Customers pay provider**
- **Peers don't pay each other**

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

Interdomain Routing: Setup

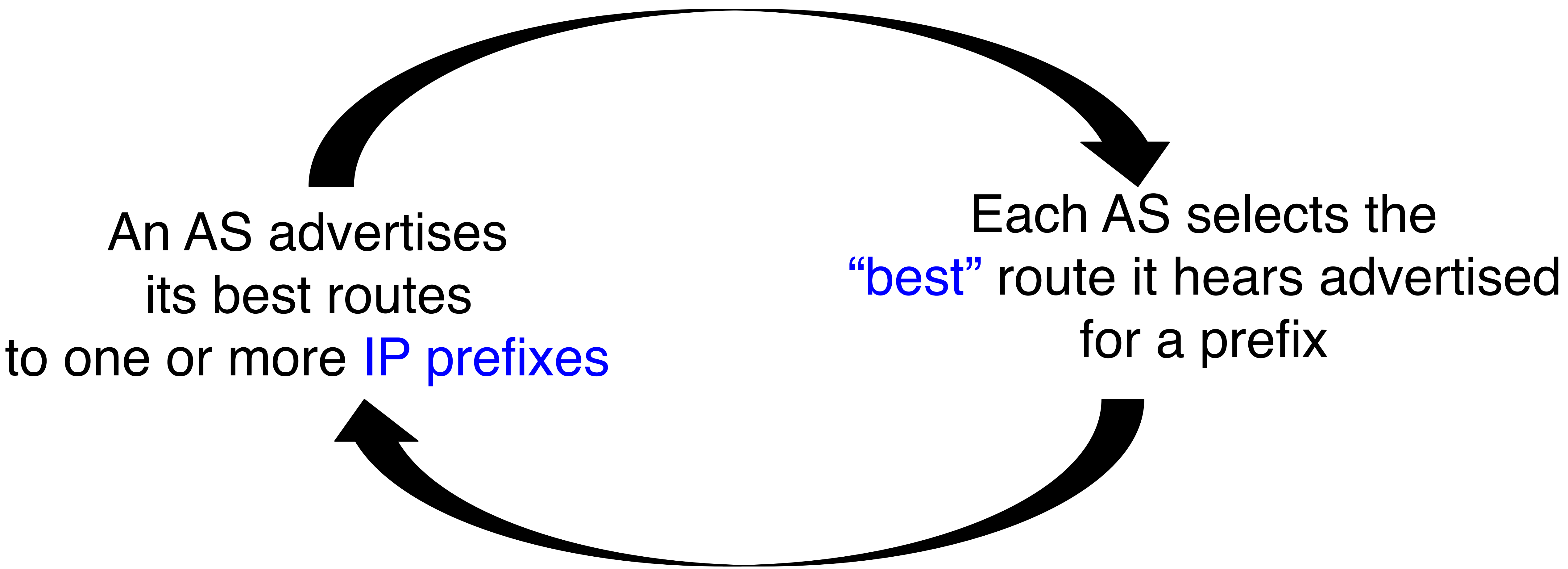
- Destinations are IP prefixes (12.0.0.0/8)

- 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

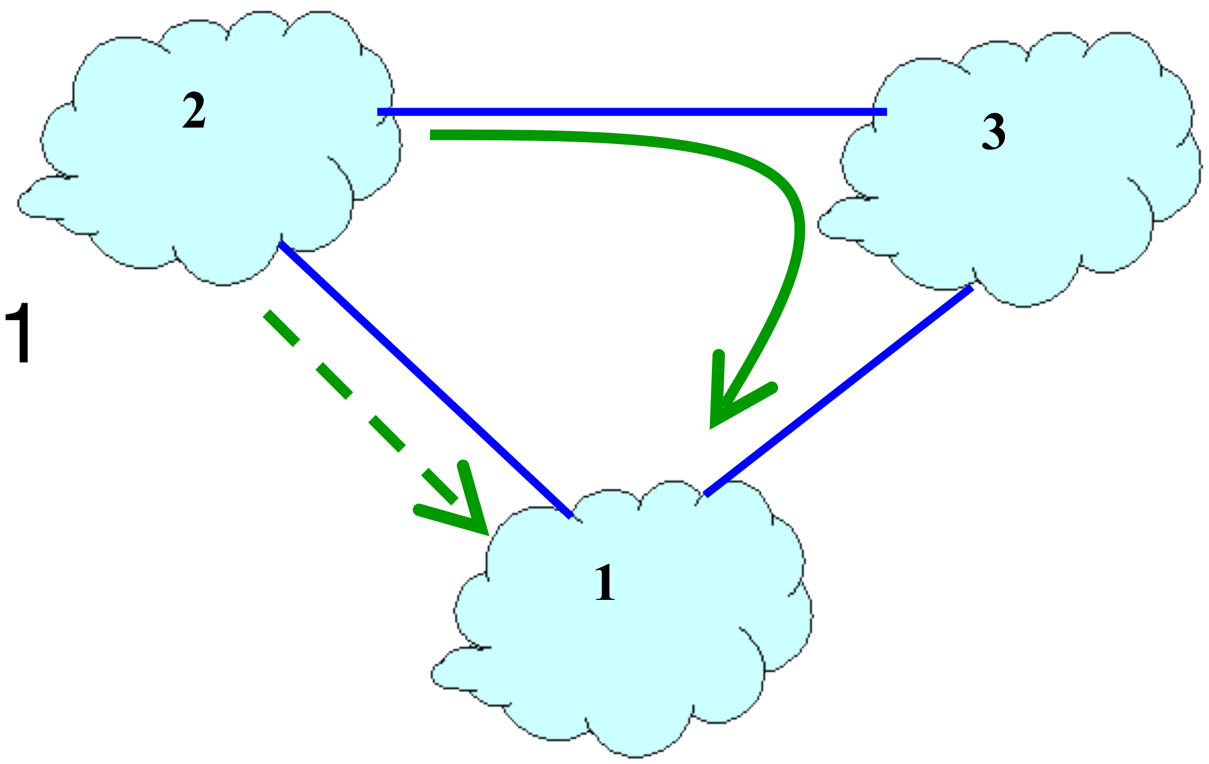
- Per-destination route advertisements
- No global sharing of network topology
- Iterative and distributed convergence on paths
- But, four key differences

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

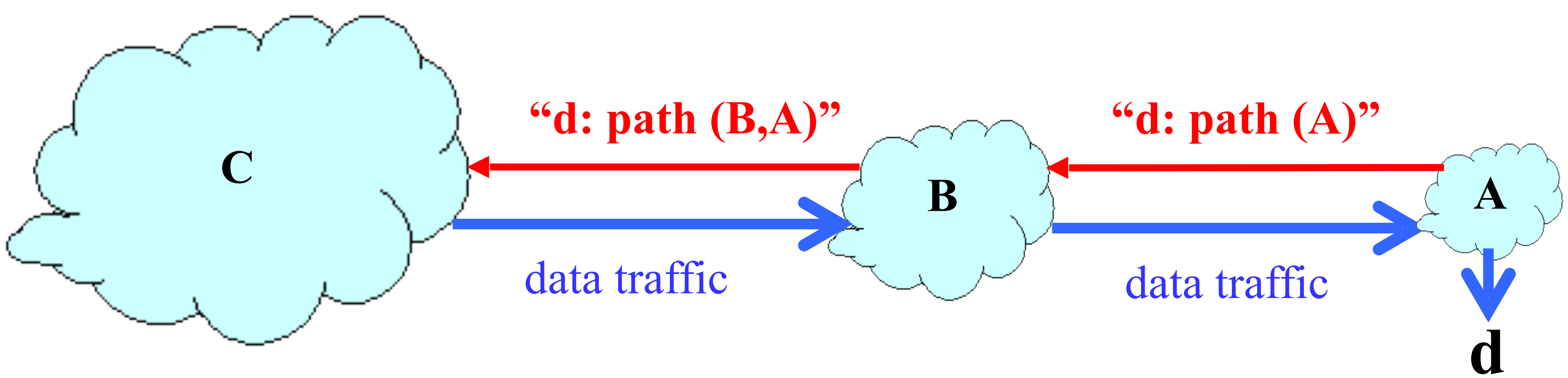


- How do we avoid loops?

BGP vs. DV

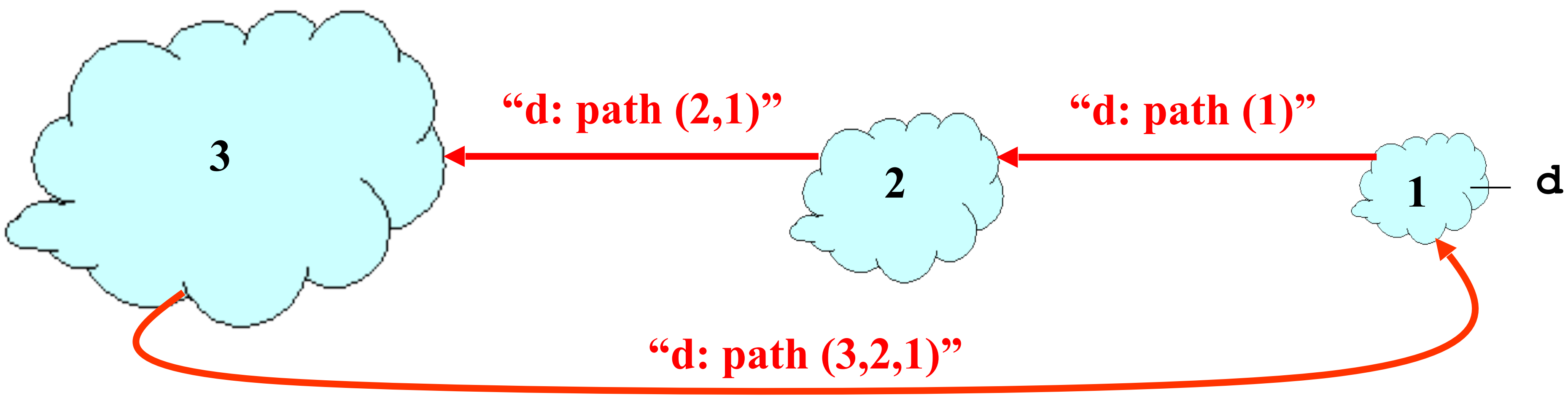
(2) Path-vector Routing

- 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

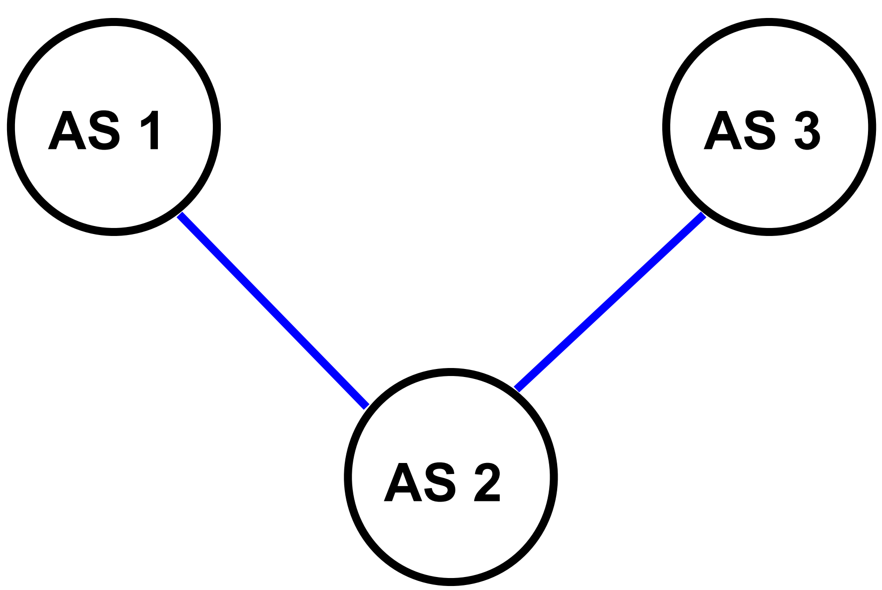
- Idea: advertise the entire path
  - Distance vector: send *distance metric* per dest. d
  - Path vector: send the *entire path* for each dest. d

- 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

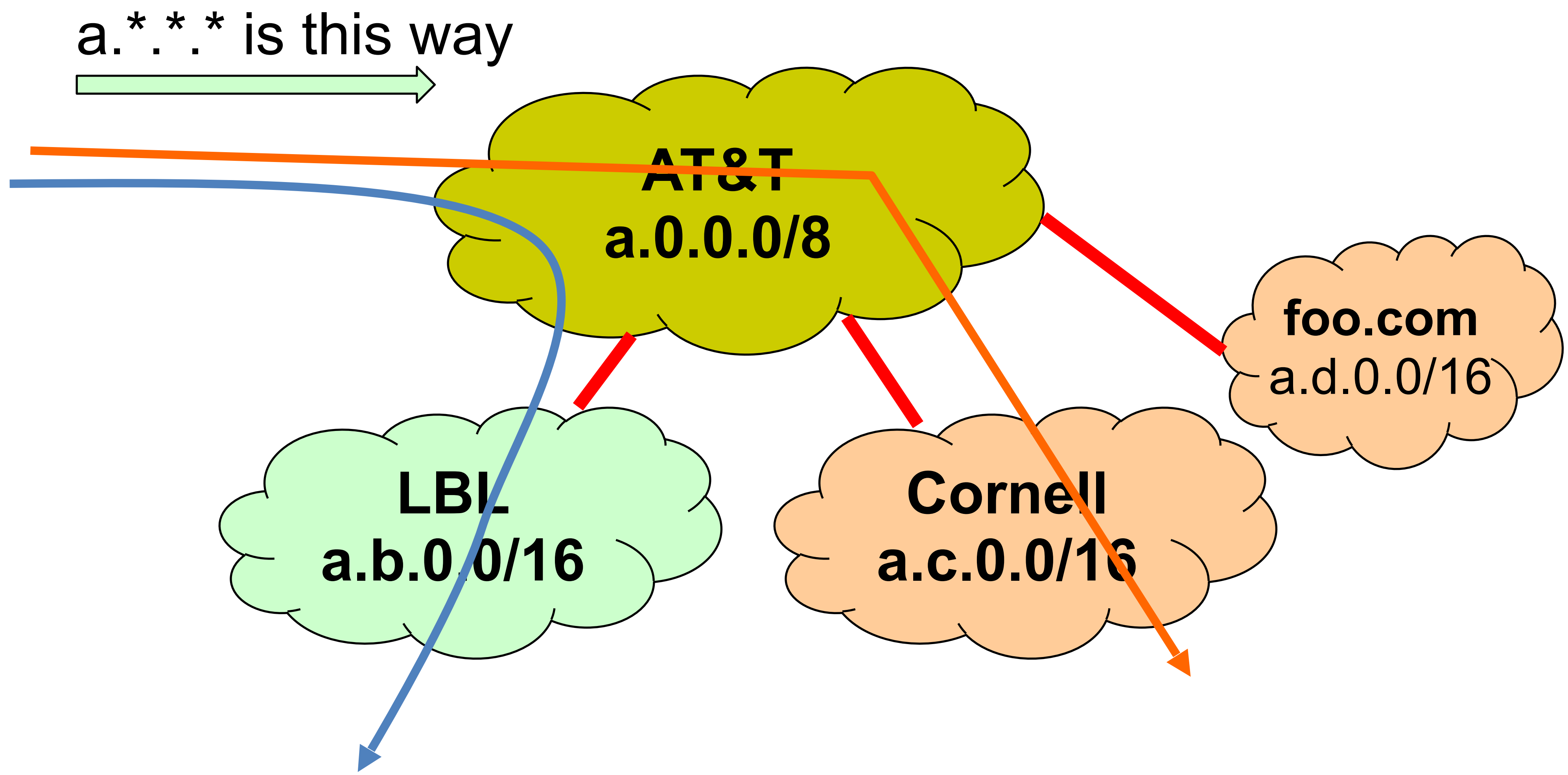


Example: AS#2 does not want to carry traffic between AS#1 and AS#3

BGP vs. DV

(4) BGP may aggregate routes

- For scalability, BGP may aggregate routes for different prefixes



BGP Outline

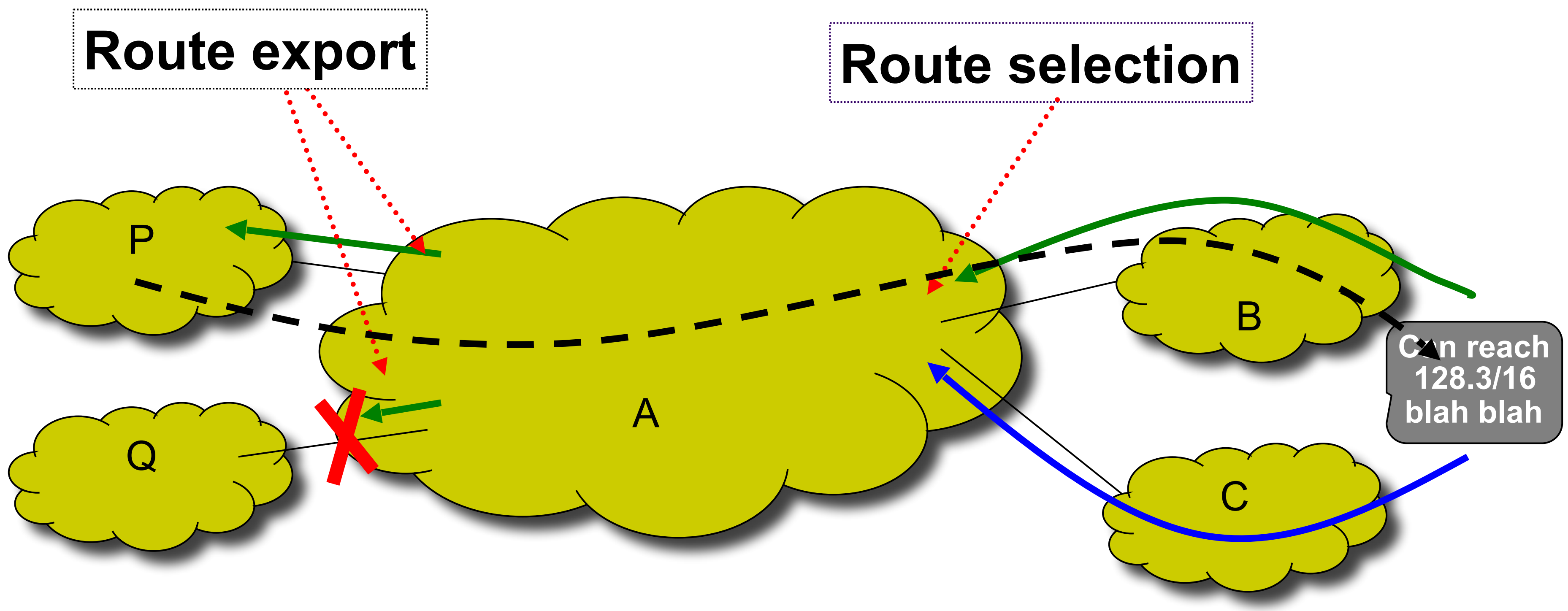
- BGP Policy
  - Typical policies and implementation

- 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