EN.601.414/614 Computer Networks

Inter-Domain Routing

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Spring 2019 (MW 3:00-4:15pm in Shaffer 301)

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https://github.com/xinjin/course-net

Final Exam

- **Time: 6pm-7:30pm, Wednesday, May 8**
- **Location: Shaffer 301**
- **Form: Closed-book**
  - Can bring TWO A4/letter papers with notes on both sides
  - Can bring a calculator
  - Anything else is prohibited
- **Focus on materials after midterm**
  - Materials before midterm will be tested, but not a focus

Recap: Link-state routing

- **Every router knows its local "link state"**
  - Router u: "(u,v) with cost=2; (u,x) with cost=1"
- **Each router floods its local link state to all other routers in the network**
  - Does so periodically or when its link state changes
- **Every router learns the entire network graph**
  - Each runs Dijkstra's Shortest-Path First (SPF) algorithm locally to compute forwarding table

Recap: Distance-vector protocol

- **Link-state routing protocol**
  - Each node broadcasts its local information
- **Distance-vector routing protocol**
  - The opposite (sort of)
  - Each node tells its neighbors about its global view

Recap: Distance vector algorithm

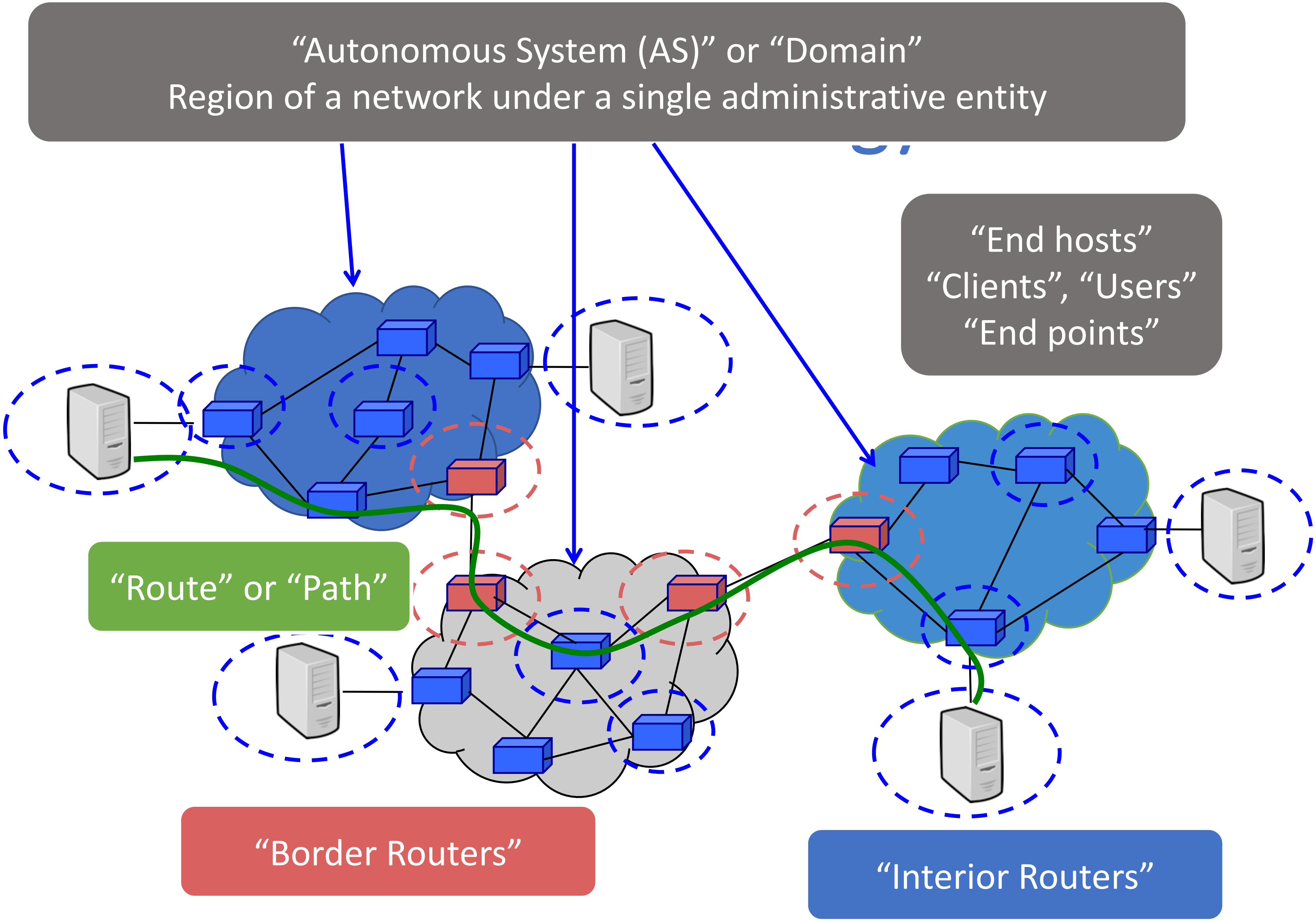
- **From time-to-time, each node sends its own distance vector estimate to neighbors**
- **When x receives new DV estimate from neighbor, it updates its own DV using B-F equation**
  - $D_x(y) \leftarrow \min_v\{c(x,v) + D_v(y)\}$ for each node $y \in N$
- **Eventually, the estimate $D_x(y)$ may converge to the actual least cost $d_x(y)$**

Recap: Similarities between LS and DV routing

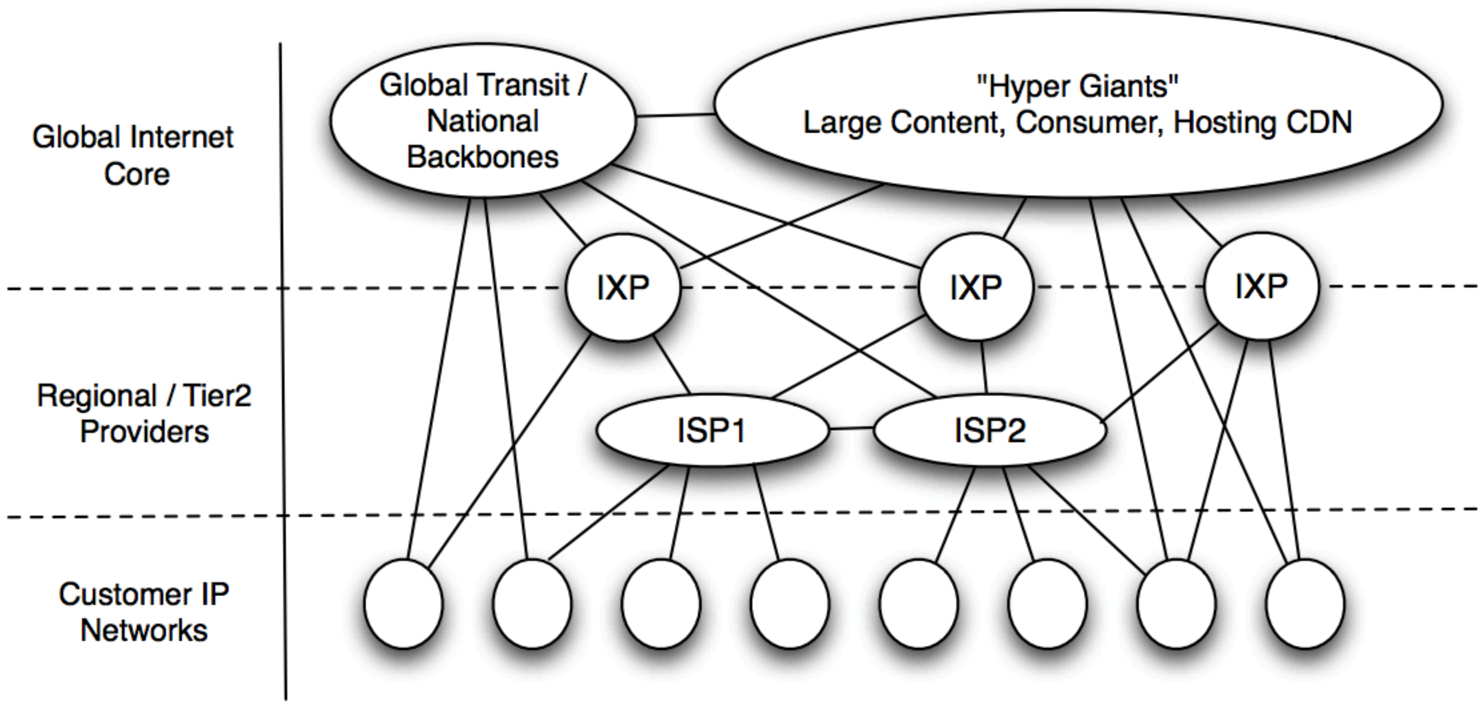
- **Both are shortest-path based routing**
  - ➢ Minimizing cost metric (link weights) a common optimization goal
    - Routers share a common view as to what makes a path "good" and how to measure the "goodness" of a path
- **Due to shared goal, commonly used inside an organization**
  - ➢ RIP and OSPF are mostly used for intra-domain routing

Agenda

- **Inter-domain routing**


“Autonomous System (AS)” or “Domain”
Region of a network under a single administrative entity
“End hosts”
“Clients”, “Users”
“End points”
“Route” or “Path”
“Border Routers”
“Interior Routers”

AS-level Internet



Internet Inter-Domain Traffic, SIGCOMM, 2010

Autonomous systems (AS)

- **An AS is a network under a single administrative control**
  - ➢Currently over 55,000 ASes
  - ➢Updated daily at http://www.cidr-report.org/as2.0/
- **ASes are sometimes called "domains"**
- **Each AS is assigned a unique identifier (ASN)**

“Intra-domain” routing: Within an AS

- **Link-State (e.g., OSPF) and Distance-Vector (e.g., RIP)**
- **Primary focus**
  - Finding least-cost paths
  - Fast convergence

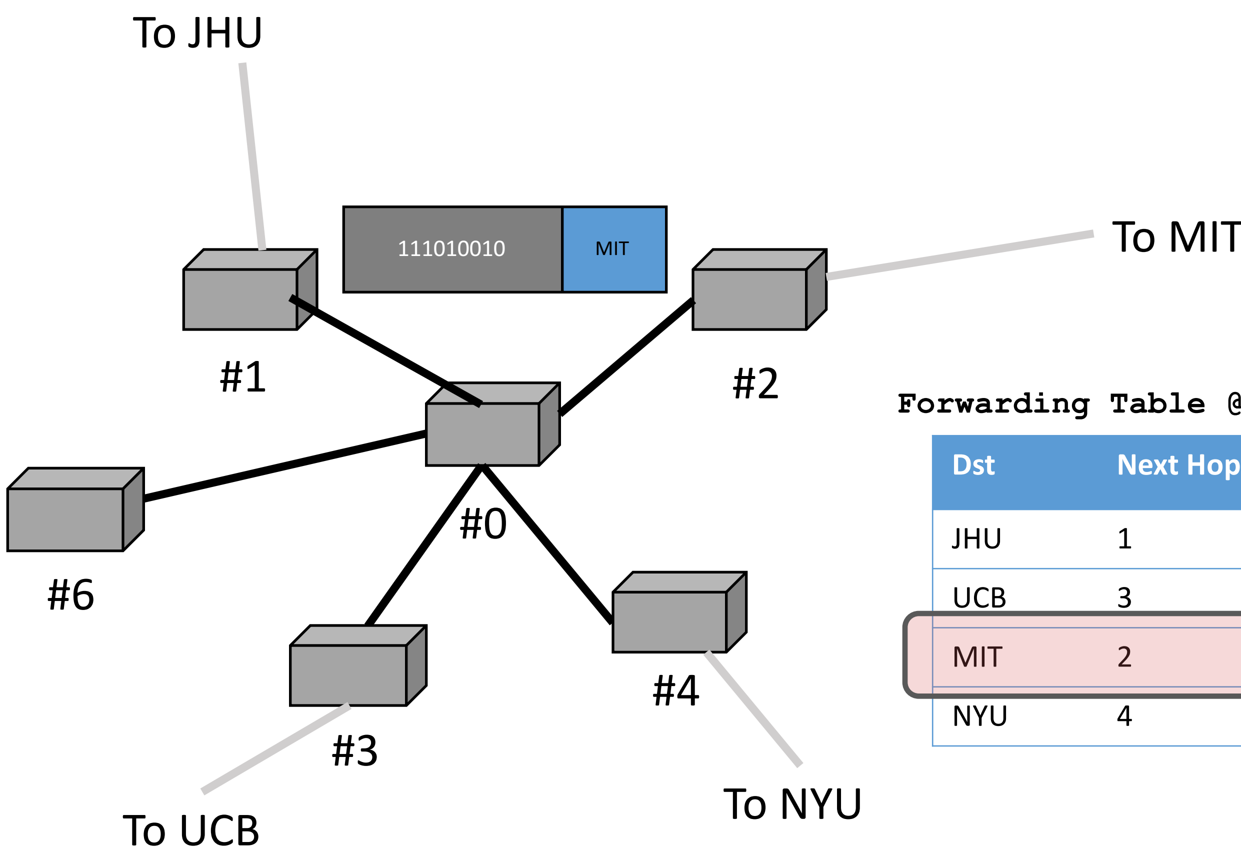
“Inter-domain” routing: Between ASes

- **Two key challenges**
  - ➢Scaling
  - ➢Administrative structure
    - Issues of autonomy, policy, privacy

Recall: Addressing (so far)

- **Each host has a unique ID**
- **No particular structure to those IDs**

Recall: Forwarding



Forwarding Table @ #0

Dst	Next Hop
JHU	1
UCB	3
MIT	2
NYU	4

Two key challenges

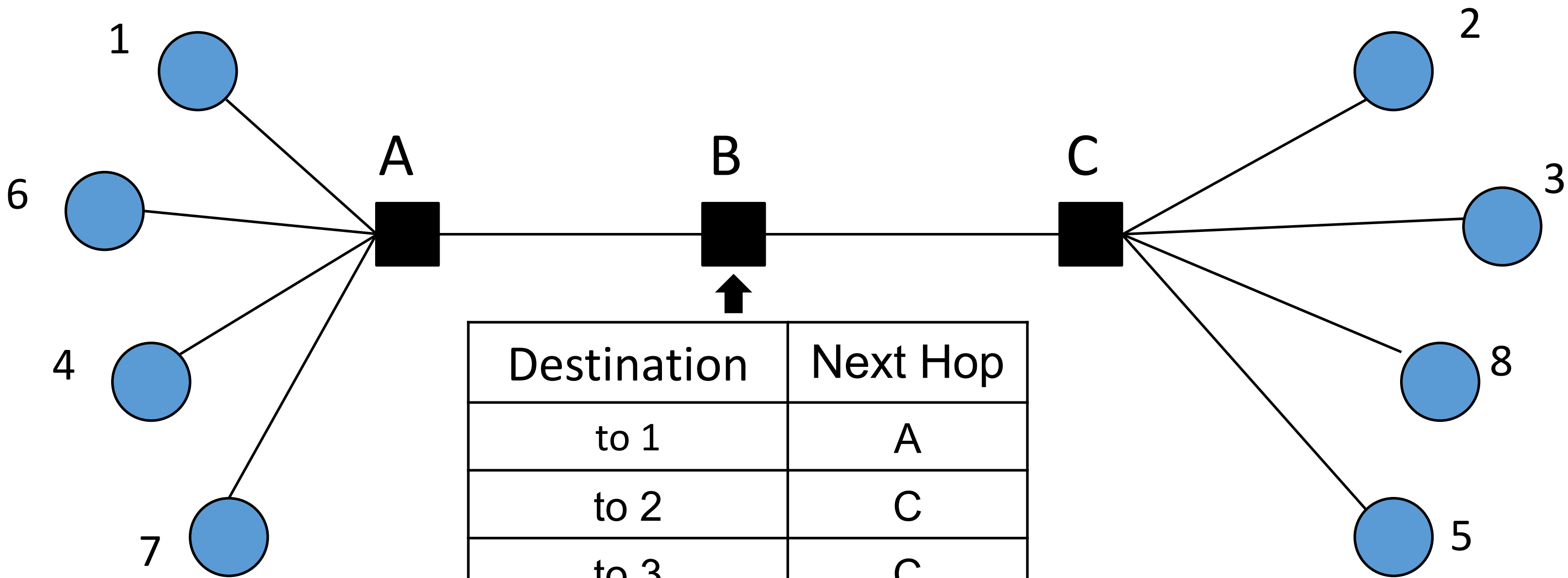
- **Scaling**
- **Administrative structure**
  - Issues of autonomy, policy, privacy

Scaling

- **A router must be able to reach any destination**
  - Given packet's destination address, lookup next hop
- **Naive: Have an entry for each destination**
  - There would be over 10^9 entries!
  - AND routing updates per destination!

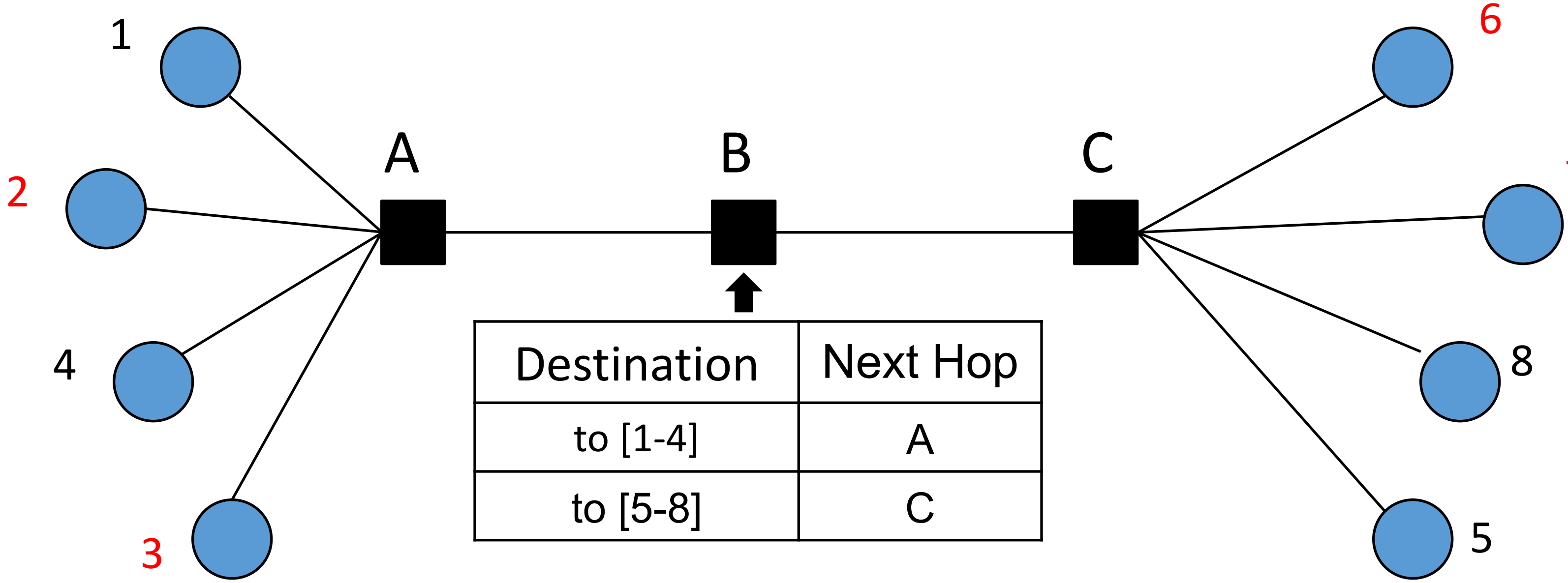
- **How can we improve scalability?**
  - We have already seen an example: longest-prefix matching

A smaller table at node B?



Destination	Next Hop
to 1	A
to 2	C
to 3	C
to 4	A
to 5	C
to 6	A
to 7	A
to 8	C

Re-number the end-systems?



Destination	Next Hop
to [1-4]	A
to [5-8]	C

- **Careful address assignment → can *aggregate* multiple addresses into one range → scalability!**
- **Akin to reducing the number of destinations**

Scaling

- **A router must be able to reach any destination**
- **Naive: Have an entry for each destination**
- **Better: Have an entry for a range of addresses**
  - ➢Can’t do this if addresses are assigned randomly!
  - ➢How addresses are allocated will matter!

- **Host addressing is key to scaling**

Two key challenges

- Scaling
- **Administrative structure**
    - ➢ Issues of autonomy, policy, privacy

Administrative structure shapes inter-domain routing

- **ASes want freedom in picking routes**
  - "My traffic can't be carried over my competitor's network"
  - "I don't want to carry A's traffic through my network"
  - Not expressible 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**
  - ➢No privacy – broadcasts all network information
  - ➢Limited autonomy – needs agreement on metric, algo
- **Distance-vector is a decent starting point**
  - ➢Per-destination updates give some control
  - ➢BUT wasn't designed to implement policy
  - ➢AND is vulnerable to loops

- **The "Border Gateway Protocol" (BGP) extends distance-vector ideas to accommodate policy**

Agenda

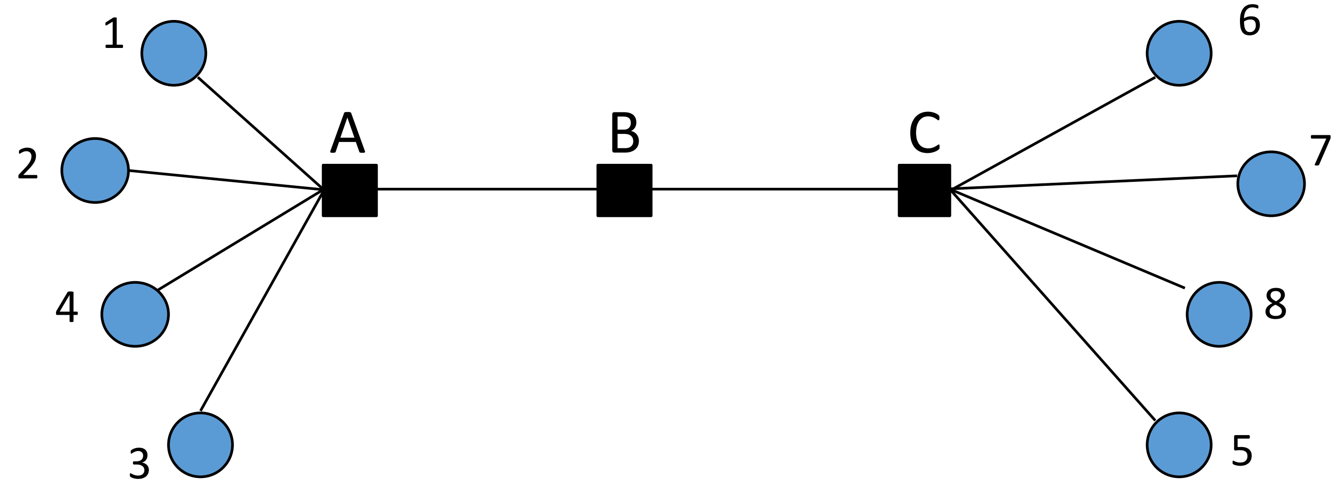
- **Inter-domain-routing**
  - ➢Addressing (Scalability)
  - ➢BGP (Autonomy, policy, privacy)
    - Context and basic ideas: today
    - Details and issues: next lecture

IP addressing

Goal of addressing: Scalable routing

- **State: Small forwarding tables at routers**
  - Much less than the number of hosts
- **Churn: Limited rate of change in routing tables**
- **Ability to aggregate addresses is crucial for both**

Aggregation works if…



- **Groups of destinations reached via the same path**
- **These groups are assigned contiguous addresses**
- **These groups are relatively stable**
- **Few enough groups to make forwarding easy**

IP addressing is hierarchical

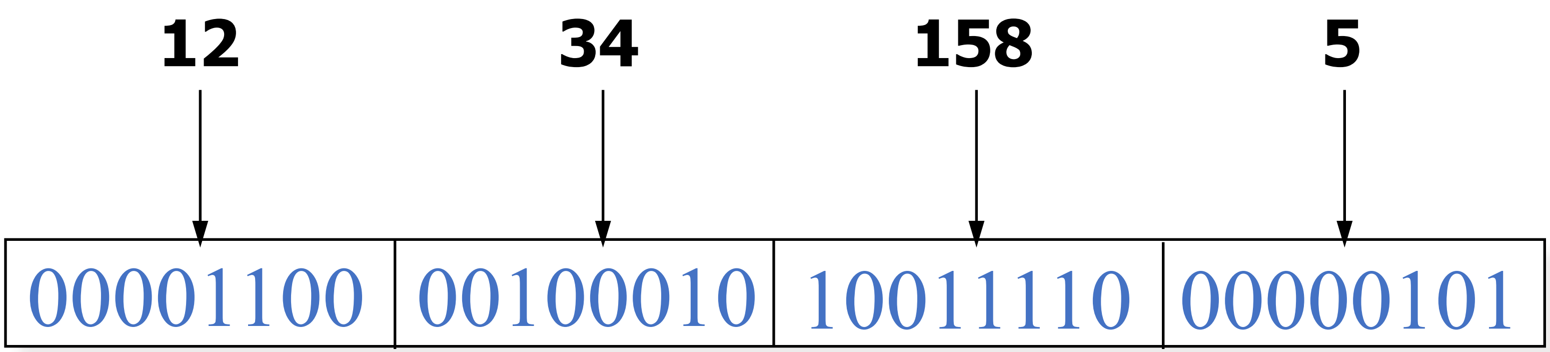
- **Hierarchical address structure**
- **Hierarchical address allocation**
- **Hierarchical addresses and routing scalability**

IP addresses (IPv4)

- **Unique 32-bit number associated with a host**

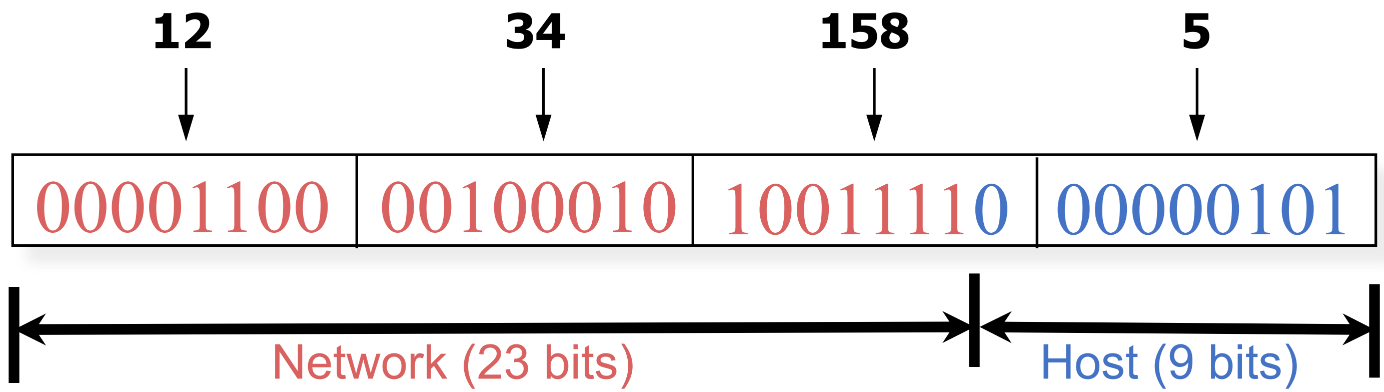
  00001100 00100010 10011110 00000101

- **Represented with the "dotted-decimal" notation**
  - e.g., 12.34.158.5



Hierarchy in IP addressing

- **32 bits are partitioned into a prefix and suffix components**
- **Prefix is the network component; suffix is the host component**



- **Inter-domain routing operates on network prefix**

CIDR: Classless inter-domain routing

- **Flexible division between network and host addresses**
- **Offers a better tradeoff between size of the routing table and efficient use of the IP address space**

CIDR example

- **Suppose a network has 50 computers**
  - ➢Allocate 6 bits for host addresses ($2^5 < 50 < 2^6$)
  - ➢Remaining 32 - 6 = 26 bits as network prefix
- **Flexible boundary means the boundary must be explicitly specified with the network address!**
  - ➢Informally, "slash 26" → 128.23.9/26
  - ➢Formally, prefix represented with a 32-bit mask: 255.255.255.192, where all network prefix bits set to "1" and host suffix bits to "0"
  - ➢Also known as subnet mask (a group of machines with the same prefix are in the same subnet)

Before CIDR: Classful addressing

- **Three classes**
  - 8-bit network prefix (Class A),
  - 16-bit network prefix (Class B), or
  - 24-bit network prefix (Class C)
- **Example: an organization needs 500 addresses.**
  - A single class C address is not enough (<500 hosts)
  - Instead, a class B address is allocated (~65K hosts)
    - Huge waste!

IP addressing is hierarchical

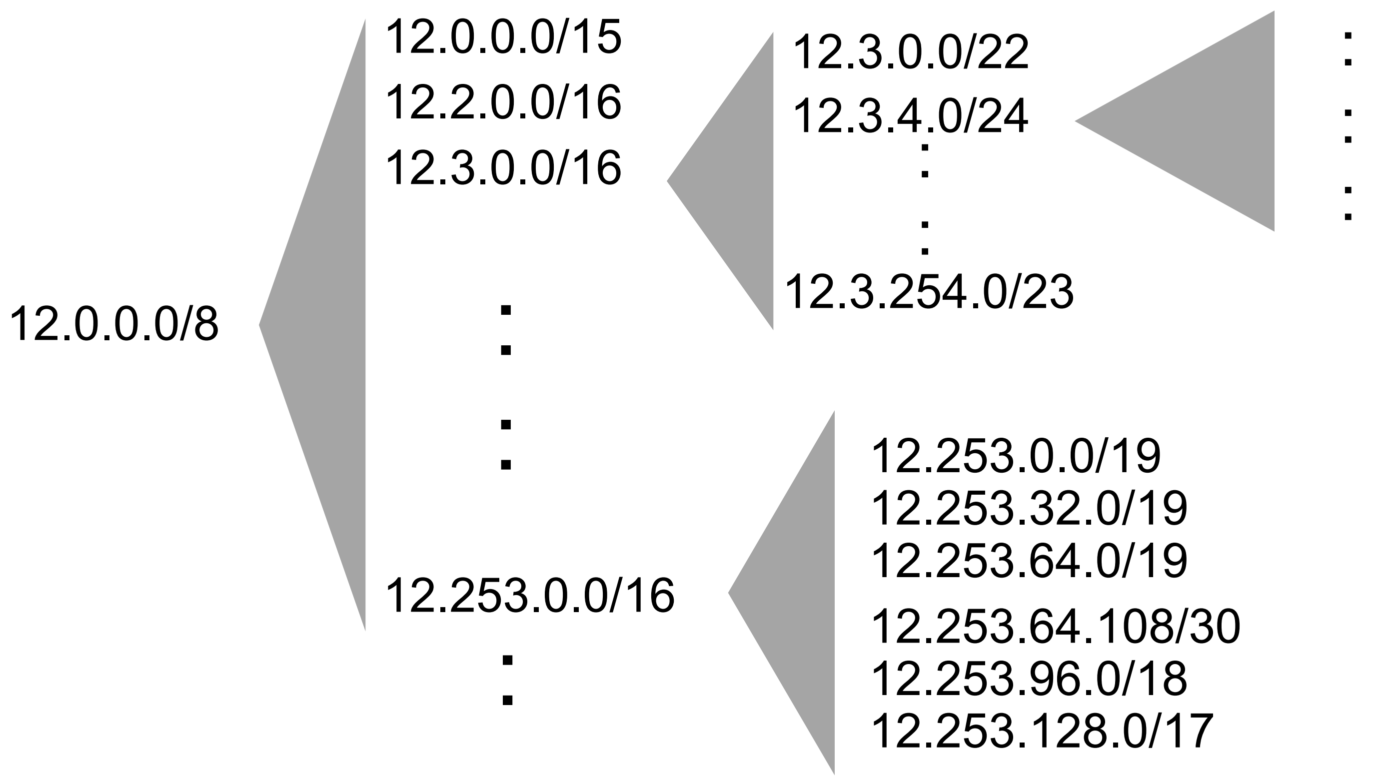
- Hierarchical address structure
- **Hierarchical address allocation**
- **Hierarchical addresses and routing scalability**

Allocation done hierarchically

- **Internet Corporation for Assigned Names and Numbers (ICANN) gives large blocks to…**
- **Regional Internet Registries, such as the American Registry for Internet Names (ARIN), which give blocks to…**
- **Large institutions (ISPs), which give addresses to…**
- **Individuals and smaller institutions**
- **FAKE Example:**
  - ICANN → ARIN → AT&T → JHU → CS

CIDR: Addresses allocated in contiguous prefix chunks

- **Recursively break down chunks as get closer to host**



FAKE example in more detail

- **ICANN gave ARIN several /8s**
- **ARIN gave AT&T one /8, 12.0/8**
  - Network Prefix: **00001100**
- **AT&T gave JHU a /16, 12.34/16**
  - Network Prefix: **0000110000100010**
- **JHU gave CS a /24, 12.34.56/24**
  - Network Prefix: **000011000010001000111000**
- **CS gave me specific address 12.34.56.78**
  - Address: **00001100001000100011100001001110**

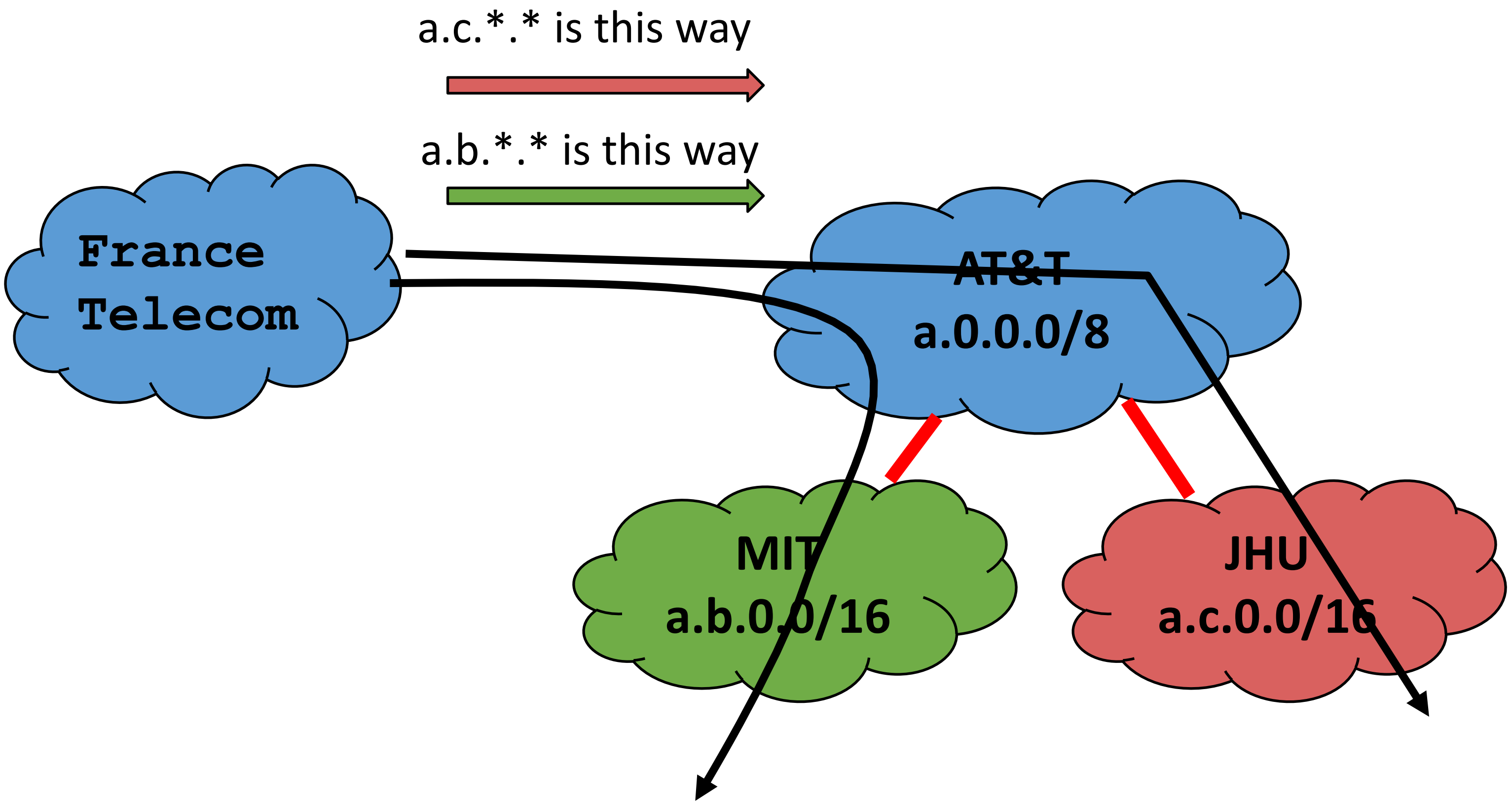
IP addressing is hierarchical

- Hierarchical address structure
- Hierarchical address allocation
- **Hierarchical addresses and routing scalability**

IP addressing → Scalable routing?

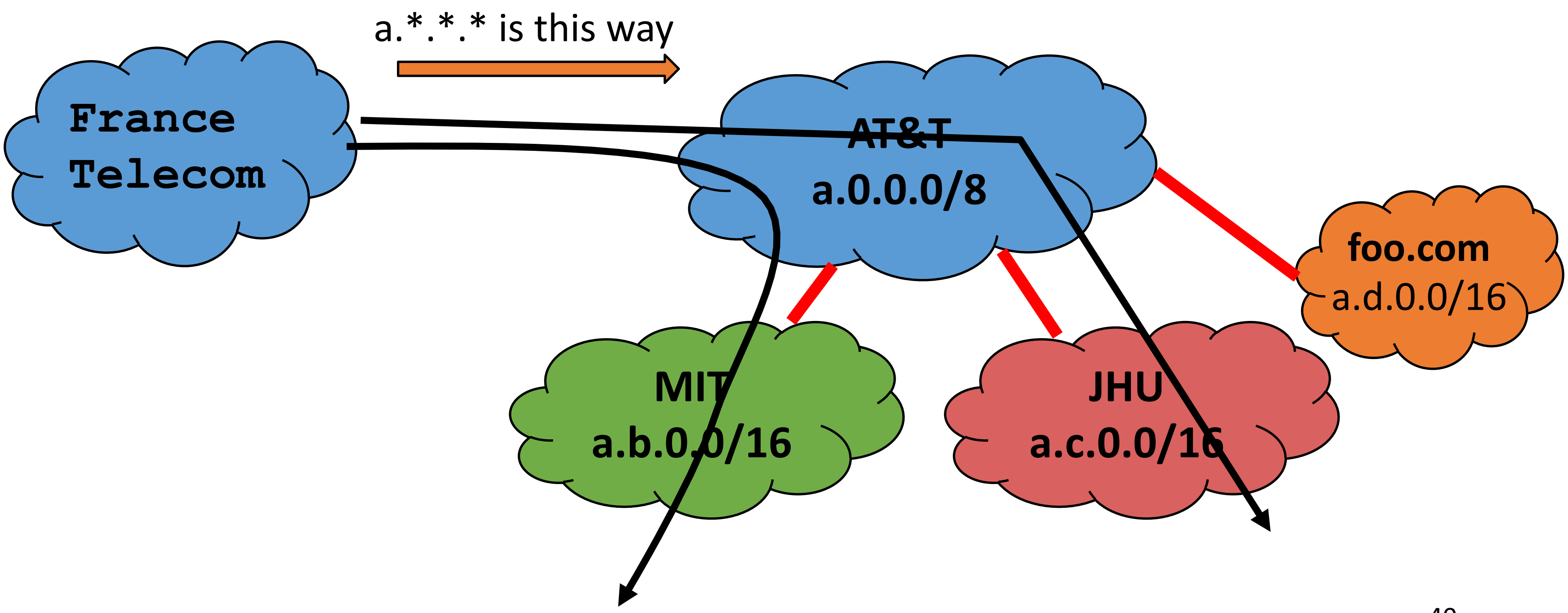
- **Hierarchical address allocation only helps routing scalability if allocation matches topological hierarchy**

IP addressing → Scalable routing?



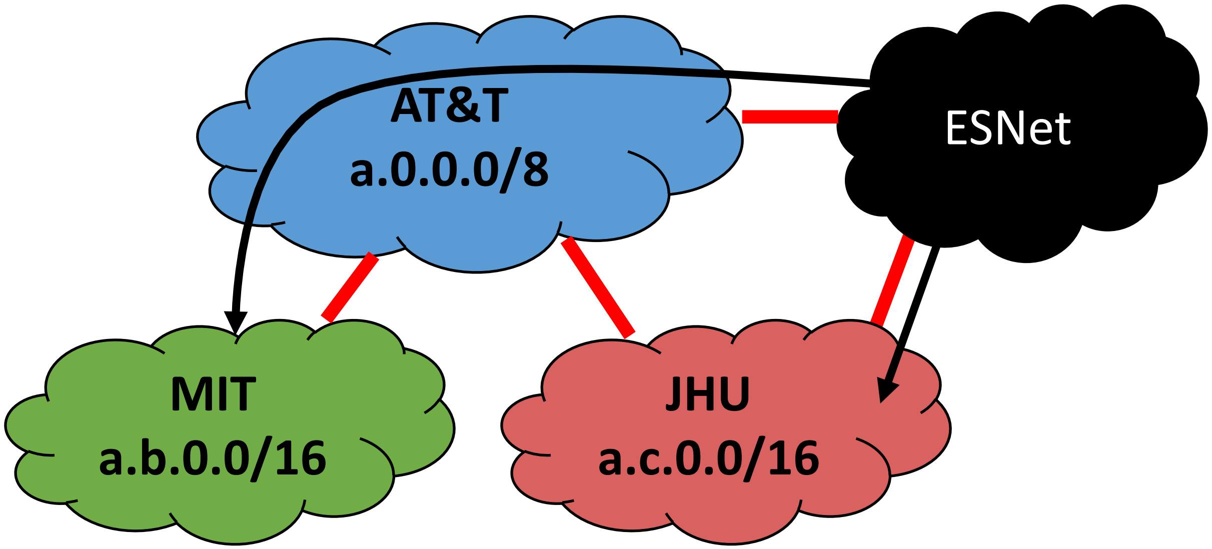
IP addressing → Scalable routing?

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.*.*



IP addressing → Scalable routing?

- **Hierarchical address allocation only helps routing scalability if allocation matches topological hierarchy**
- **May not be able to aggregate addresses for "multi-homed" networks**
  - A multi-homed network is connected to more than one ASes for fault-tolerance, load balancing, etc.

BGP: Border Gateway Protocol

BGP (Today)

- **The role of policy**
  - ➢What we mean by it
  - ➢Why we need it
- **Overall approach**
  - ➢Four non-trivial changes to DV

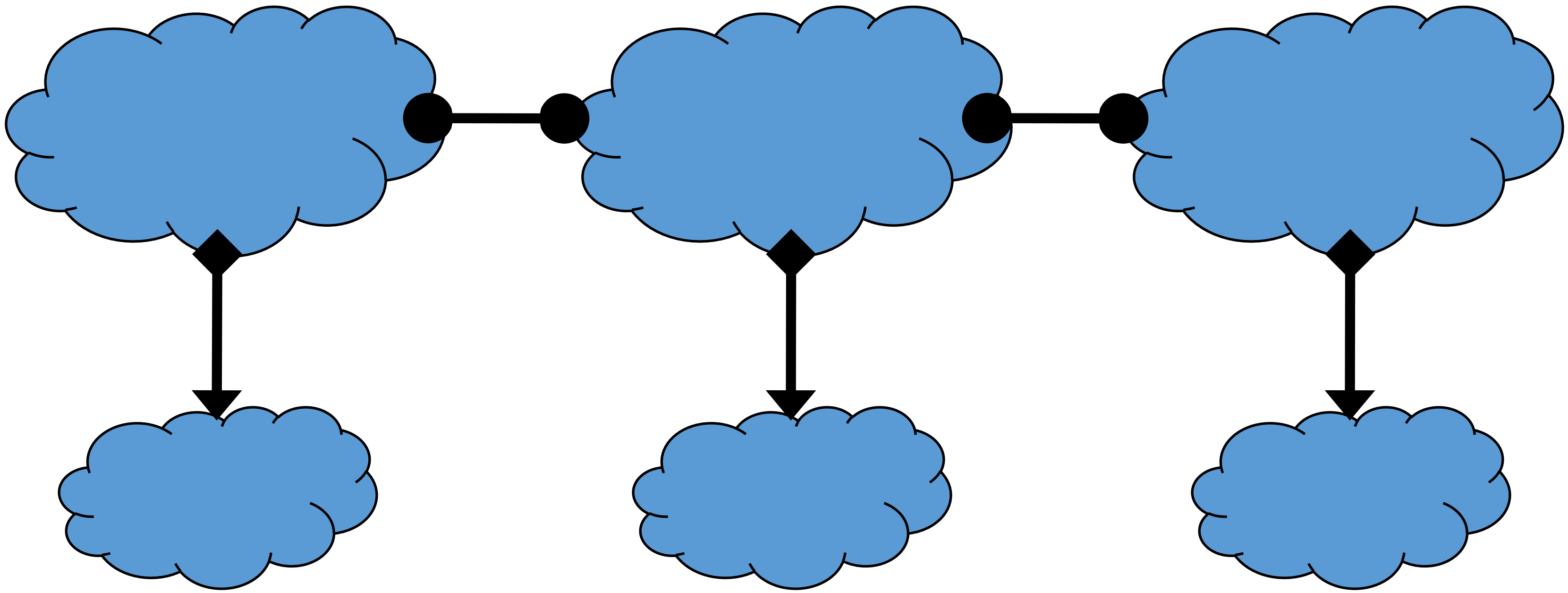
Administrative structure shapes Inter-domain routing

- **ASes want freedom to pick routes based on policy**
- **ASes want autonomy**
- **ASes want privacy**

Topology & policy shaped by inter-AS business relationship

- **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

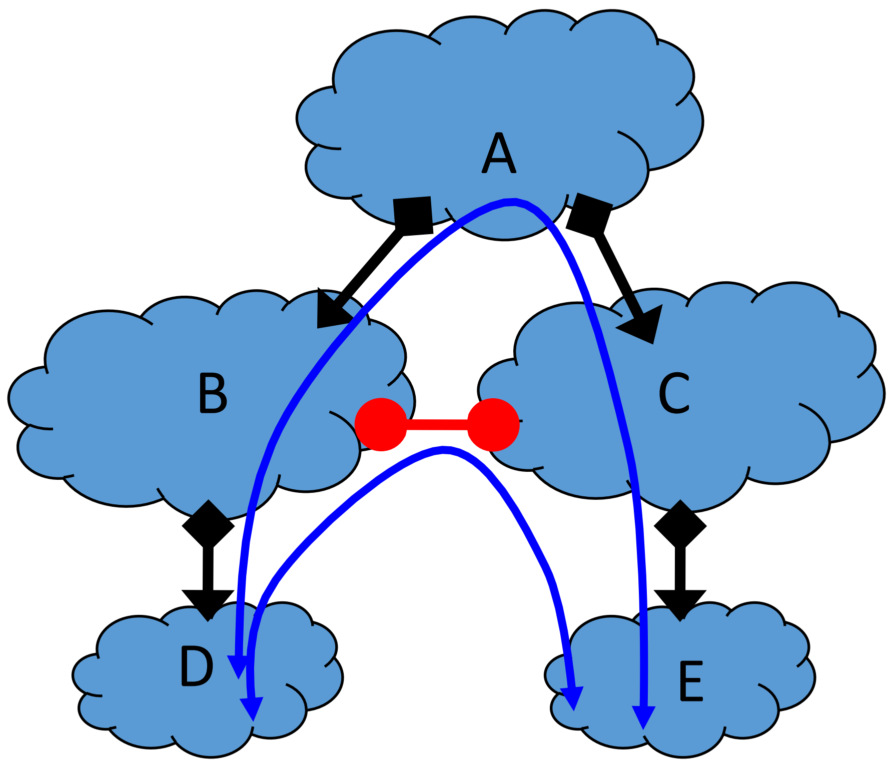
provider ◆——▶ customer

peer ●——● peer

Business implications

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

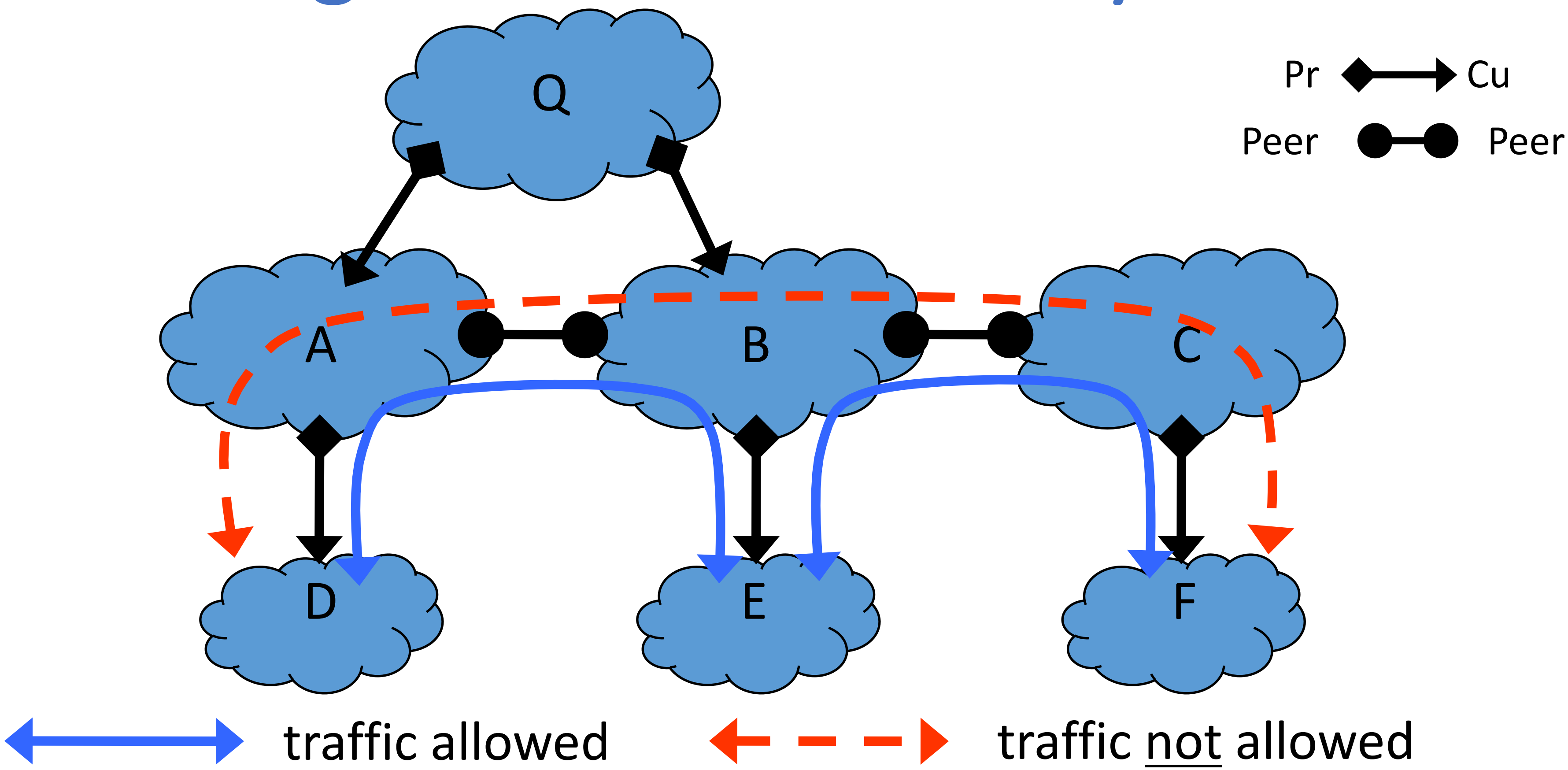
Why peer?



D and E communicate a lot

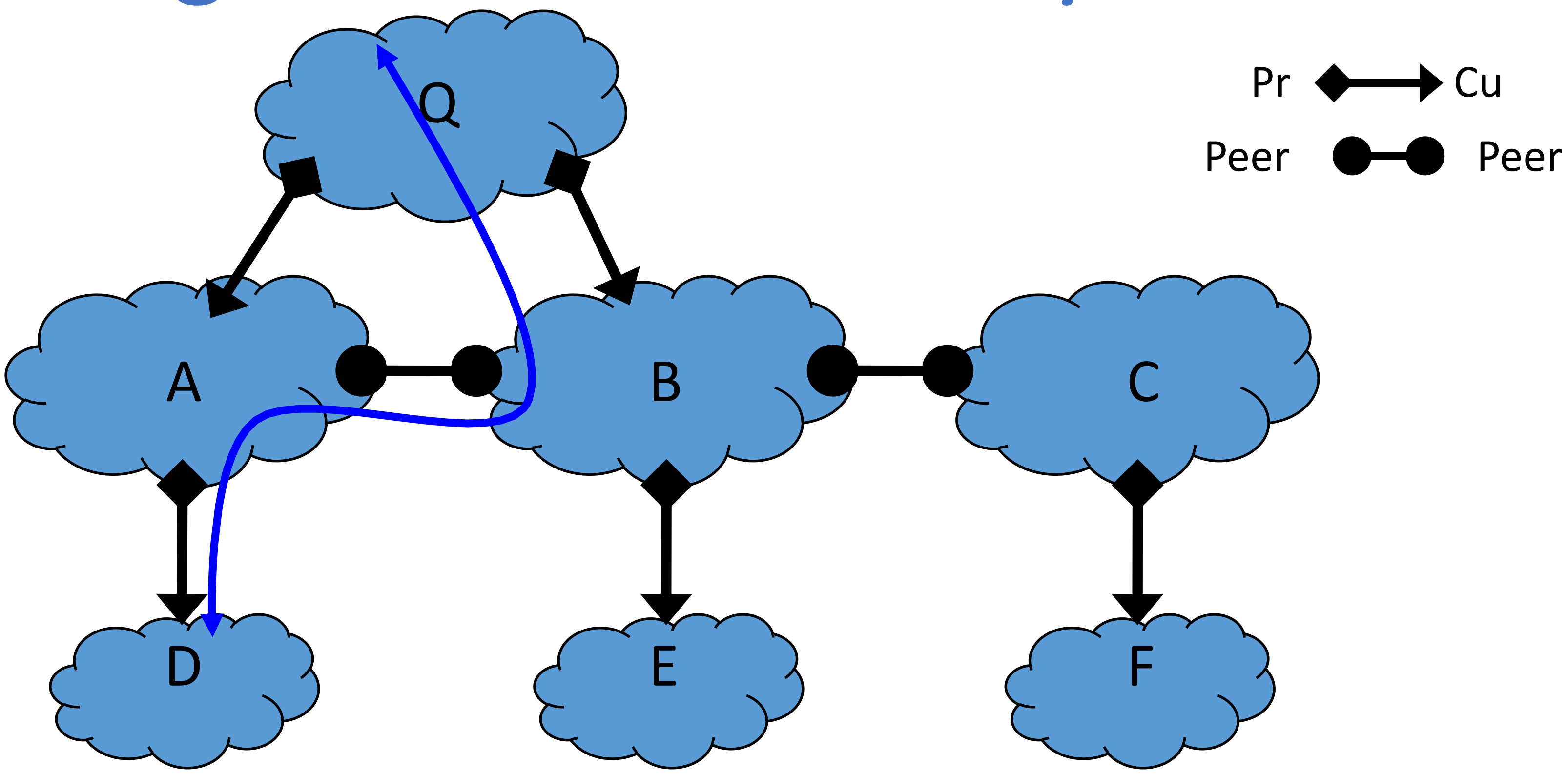
Peering saves B *and* C money

Routing follows the money!



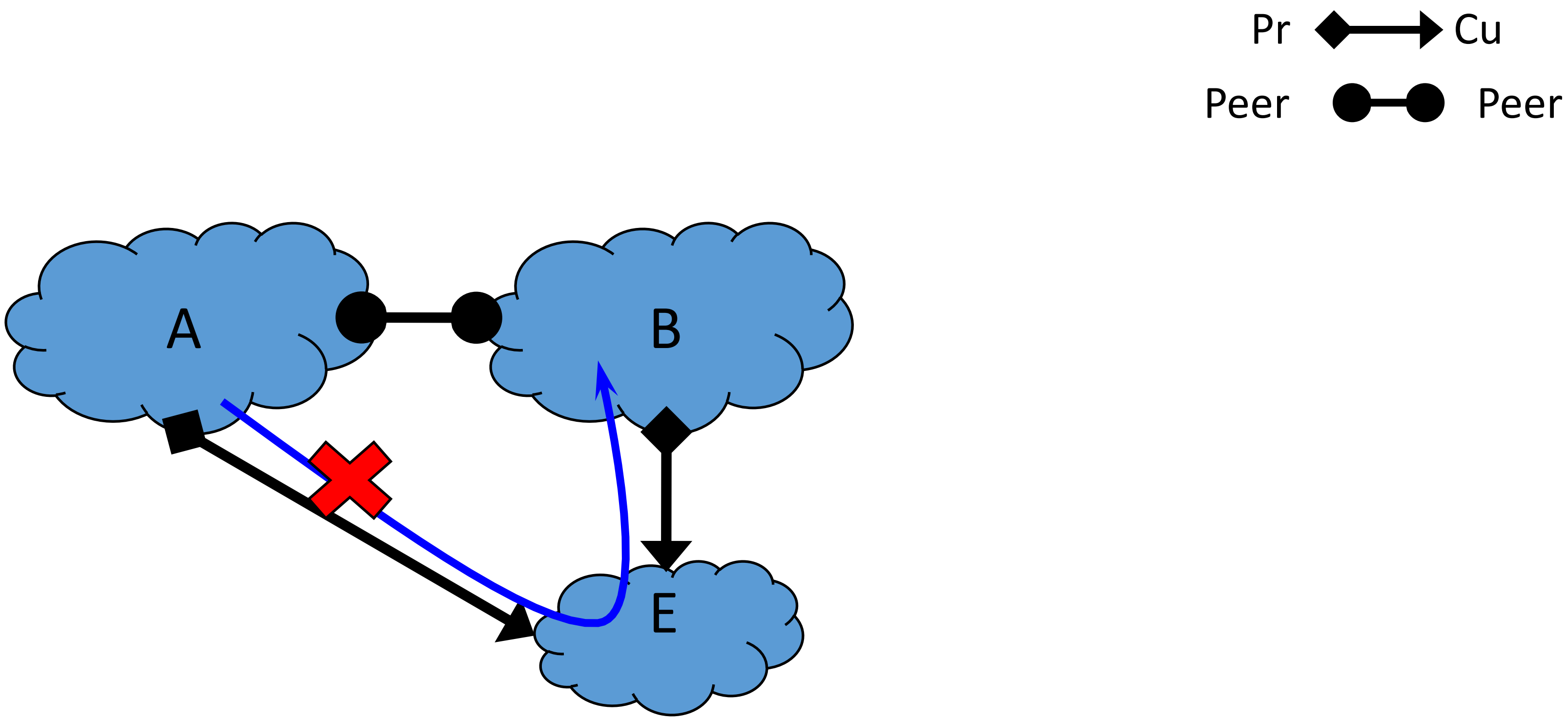
- ASes provide “transit” between their customers
- Peers do not provide transit between other peers

Routing follows the money!



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

Routing follows the money!



- Routes are "valley" free (more details later)

In short

- **AS topology reflects business relationships between ASes**
- **Business relationships between ASes impact which routes are acceptable**

BGP (Today)

- The role of policy
  - What we mean by it
  - Why we need it
- **Overall approach**
  - Four non-trivial changes to DV

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 Inter-domain routing protocol**
  - Implemented by AS border routers

BGP: Basic idea

An AS advertises ("exports") its best routes to one or more IP prefixes

Each AS selects the "best" route it hears advertised for a prefix

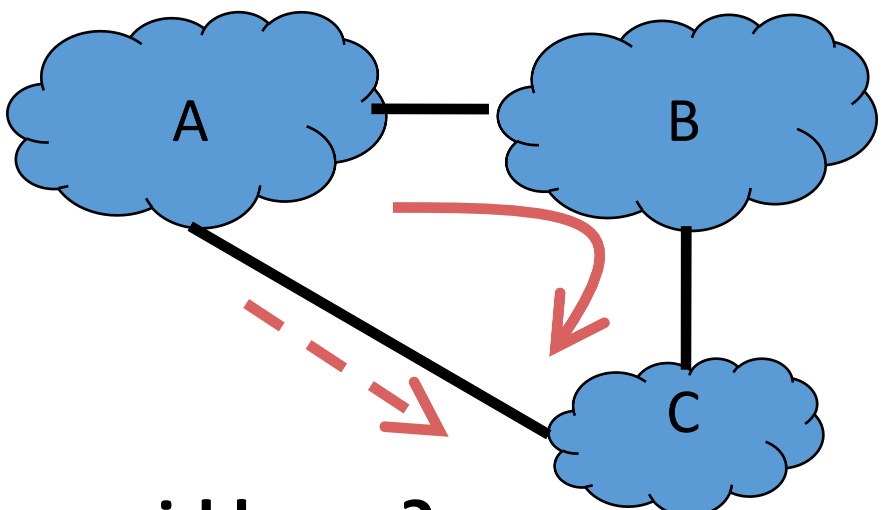
You've heard this story before!

BGP inspired by Distance-Vector

- **Per-destination route advertisements**
- **No global sharing of network topology information**
- **Iterative and distributed convergence on paths**
- **With four crucial differences!**

BGP & DV differences: (1) Not picking shortest-path routes

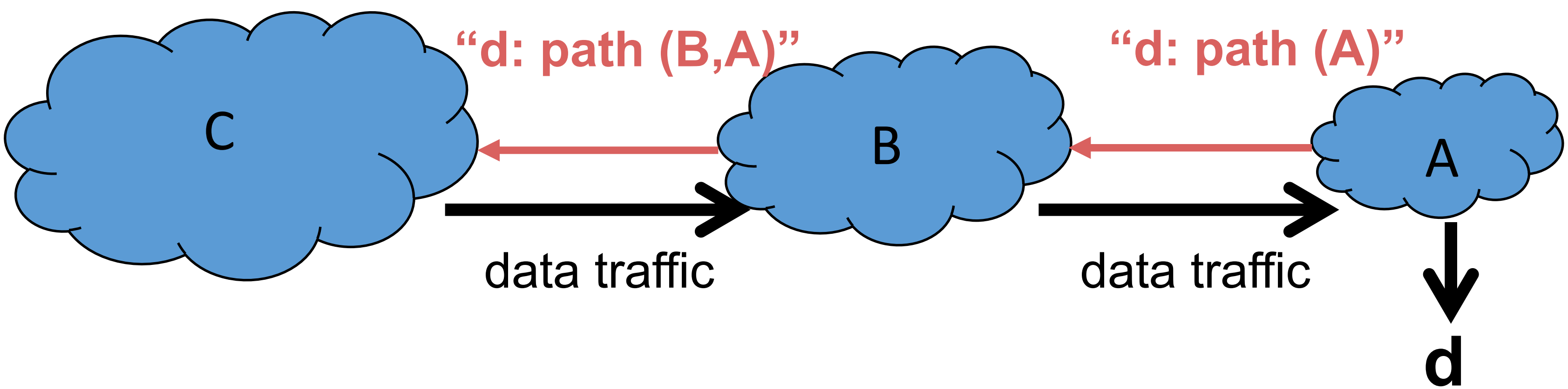
- **BGP selects the best route based on policy, not shortest distance (i.e., least-cost)**
- **AS A may prefer "A,B,C" over "A,C"**



- **How do we avoid loops?**

BGP & DV differences:
(2) Path-Vector routing

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

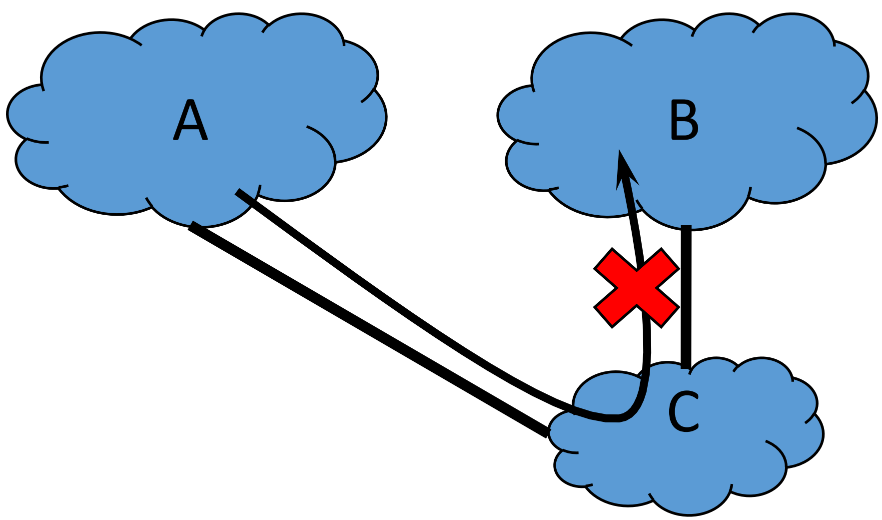


BGP & DV differences:
(2) Path-Vector routing

- **Key idea: advertise the entire path**
  - Distance vector: send distance metric per destination
  - Path vector: send the entire path for each destination
- **Benefits**
  - Loop avoidance is straightforward (simply discard paths with loops)
  - Flexible and expressive policies based on entire path

BGP & DV differences: (3) Selective route advertisement

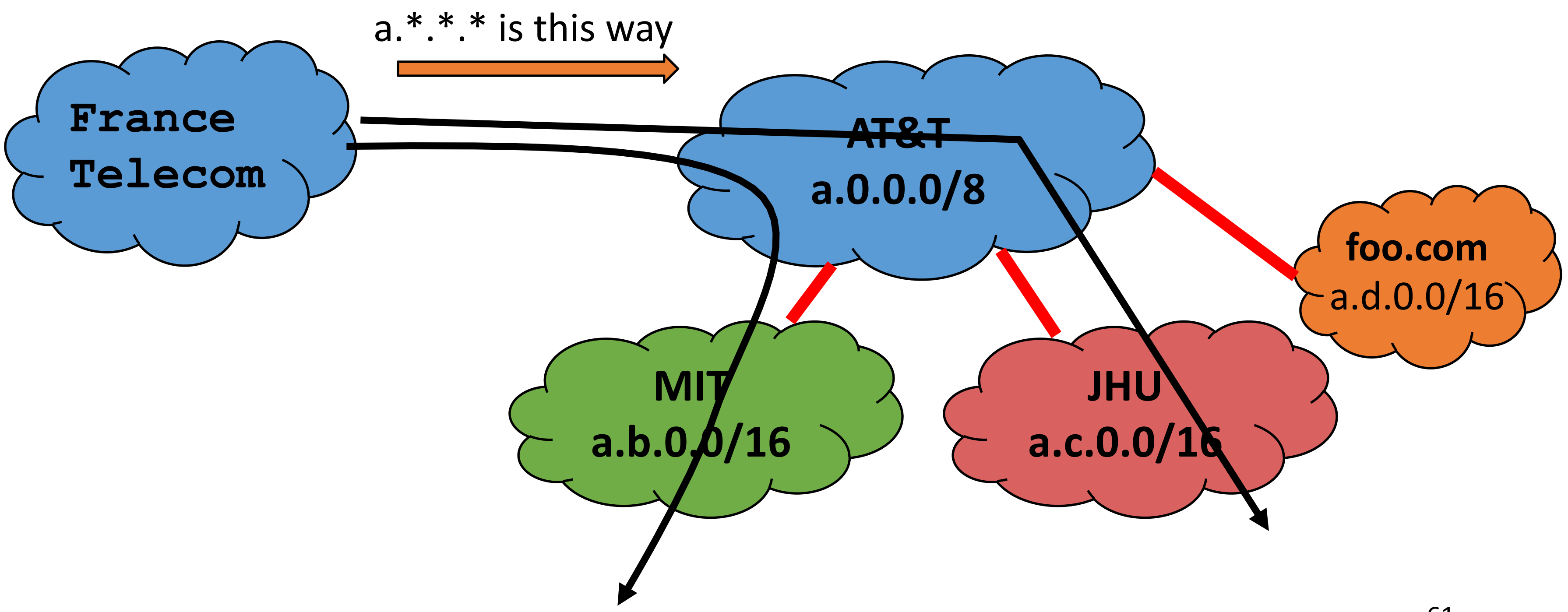
- **For policy reasons, an AS may choose not to advertise a route to a destination**
- **Hence, reachability is not guaranteed even if graph is physically connected**



AS-C does not want to carry traffic to AS-B

BGP & DV differences:
(4) BGP may aggregate routes

- **For scalability, BGP may aggregate routes for different prefixes**



Summary

- **Two key challenges in inter-domain routing**
  - ➢ Scaling (Addressing)
  - ➢ Administrative structure (BGP)
    - Issues of autonomy, policy, privacy

- **Next lecture: BGP policies, protocol, and challenges**

Thanks!
Q&A