IP Routing: Interdomain

CS/ECE 438: Spring 2014

Instructor: Matthew Caesar

http://courses.engr.illinois.edu/cs438/

Internet Routing

- So far, only considered routing within a domain

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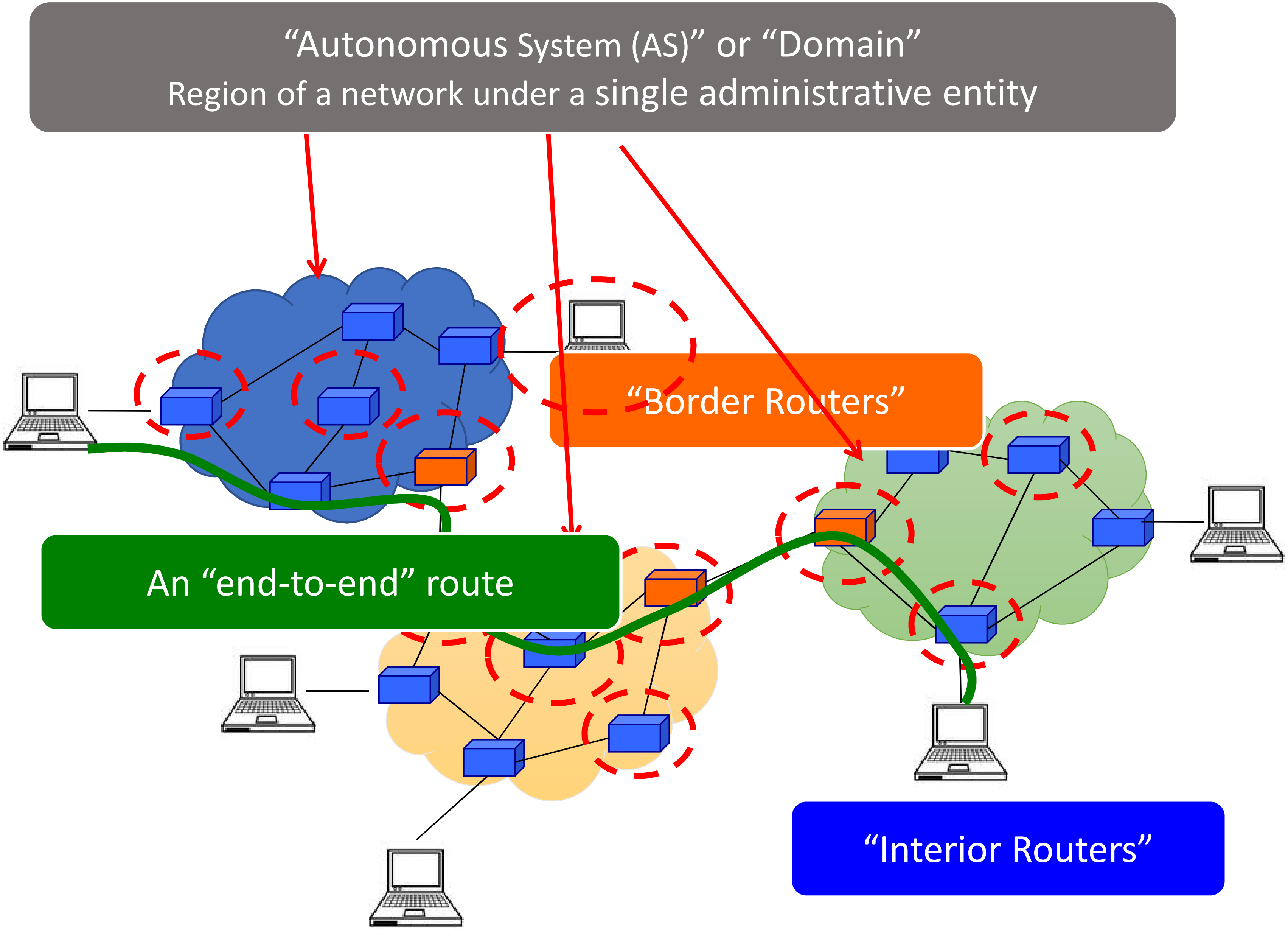
- Many issues can be ignored in this setting because there is central administrative control over routers
  - Issues such as *autonomy*, *privacy*, *policy*
- **But the Internet is more than a single domain**


"Autonomous System (AS)" or "Domain"
Region of a network under a single administrative entity
"Border Routers"
An "end-to-end" route
"Interior Routers"

Autonomous Systems (AS)

- AS is a network under a single administrative control
  - currently over 30,000 ASes
  - Think AT&T, France Telecom, UCB, IBM, *etc.*
- ASes are sometimes called “domains”.
  - Hence, “interdomain routing”
- Each AS is assigned a unique identifier
  - 16 bit AS Number (ASN)

Routing between ASes

Two key challenges

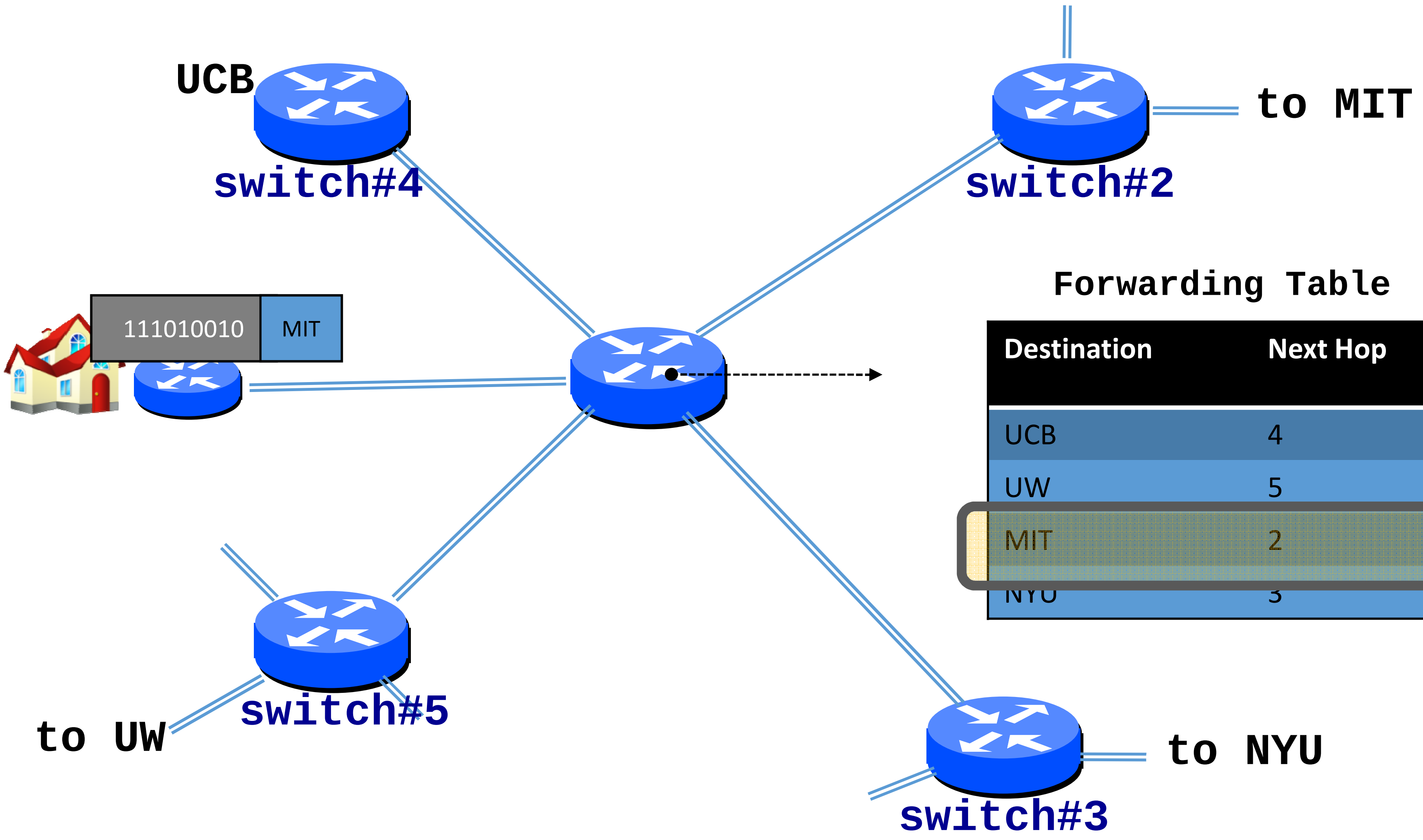
- Scaling

- Administrative structure
  - Issues of autonomy, policy, privacy

Recall From Lecture#4

- Assume each host has a unique ID
- No particular structure to those IDs

Recall Also...



Forwarding Table

Destination	Next Hop
UCB	4
UW	5
MIT	2
NYU	3

Scaling

- Every router must be able to forward packets to *any* destination
  - Given address, it needs to know "next hop" (table)
- Naive: Have an entry for each address
  - There would be over 10^8 entries!
  - And routing updates per destination!
- Any ideas on how to improve scalability?

Scaling

- Every router must be able to forward based on *any* destination address
  - Given address, it needs to know "next hop" (table)
- Naive: Have an entry for each address
  - There would be 10^8 entries!
  - And routing updates per destination!
- Better: Have an entry for a range of addresses
  - But can't do this if addresses are assigned randomly
- Addresses allocation is a big deal!

Host **addressing is key to scaling**

Two Key Challenges

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

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”*
  - Not expressible as Internet-wide “shortest path”!

- 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 -- global sharing of all network information (neighbors, policies)
- LS limits autonomy -- need agreement on metric, algorithm
- DV is a decent starting point
  - per-destination advertisement gives providers a hook for finer-grained control over whether/which routes to advertise
  - but DV wasn't designed to implement policy

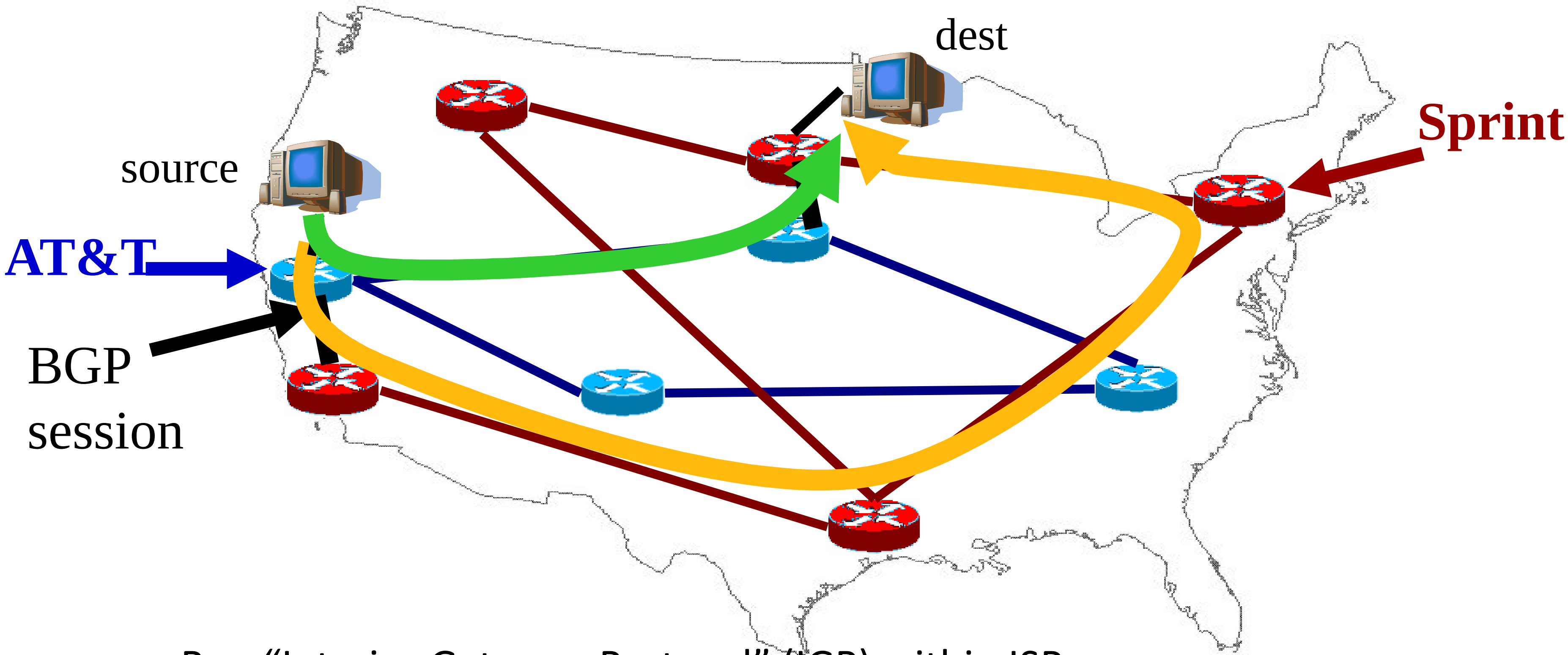
The "Border Gateway Protocol" (BGP) extends distance-vector ideas to accommodate policy

Shortest-path forwarding isn't enough

- In the real world, ISPs want to influence path selection
  - Load balance traffic, prefer cheaper paths, avoid untrusted routes, give preferential service, block reachability, limit external control over path selection decisions

- One trick: change the "cost" used to compute shortest paths
- Another trick: filter routes from being received from/advertised to certain neighbors

Intra- vs. Inter-domain routing



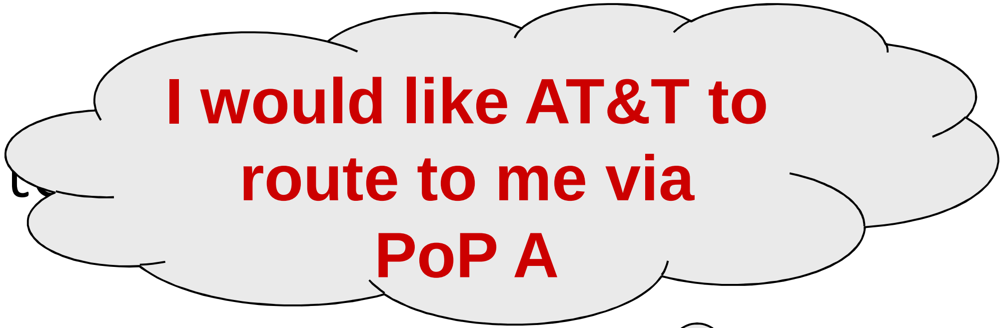
- Run “Interior Gateway Protocol” (IGP) within ISPs
  - OSPF, IS-IS, RIP
- Use “Border Gateway Protocol” (BGP) to connect ISPs
  - To reduce costs, peer at exchange points (AMS-IX, MAE-EAST)

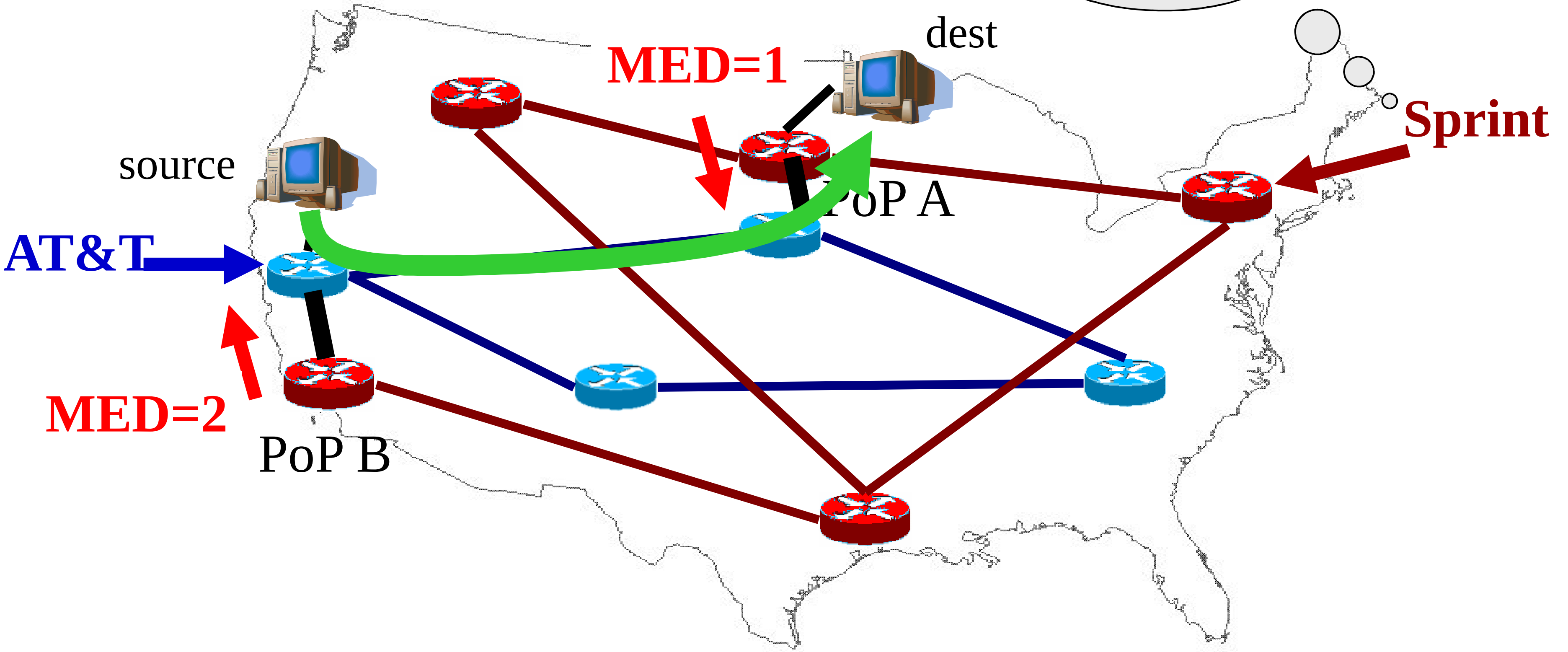
Changing the "cost" of paths

Step	Attribute	Controlled by local or neighbor AS?
1.	Highest LocalPref	local
2.	Lowest AS path length	neighbor
3.	Lowest origin type	neither
4.	Lowest MED	neighbor
5.	eBGP-learned over iBGP-learned	neither
6.	Lowest IGP cost to border router	local
7.	Lowest router ID (to break ties)	neither

- ISPs have a lot of different kinds of policies
  - Could make cost a linear combination of different metrics
  - More expressive: have several "costs" per link
- Main idea: append "attributes" to updates
- Can set preferences (or filter the route) based on set of attributes contained in update
  - Hard-coded "decision process" orders importance of attributes
  - This process can be influenced by changing values of attributes

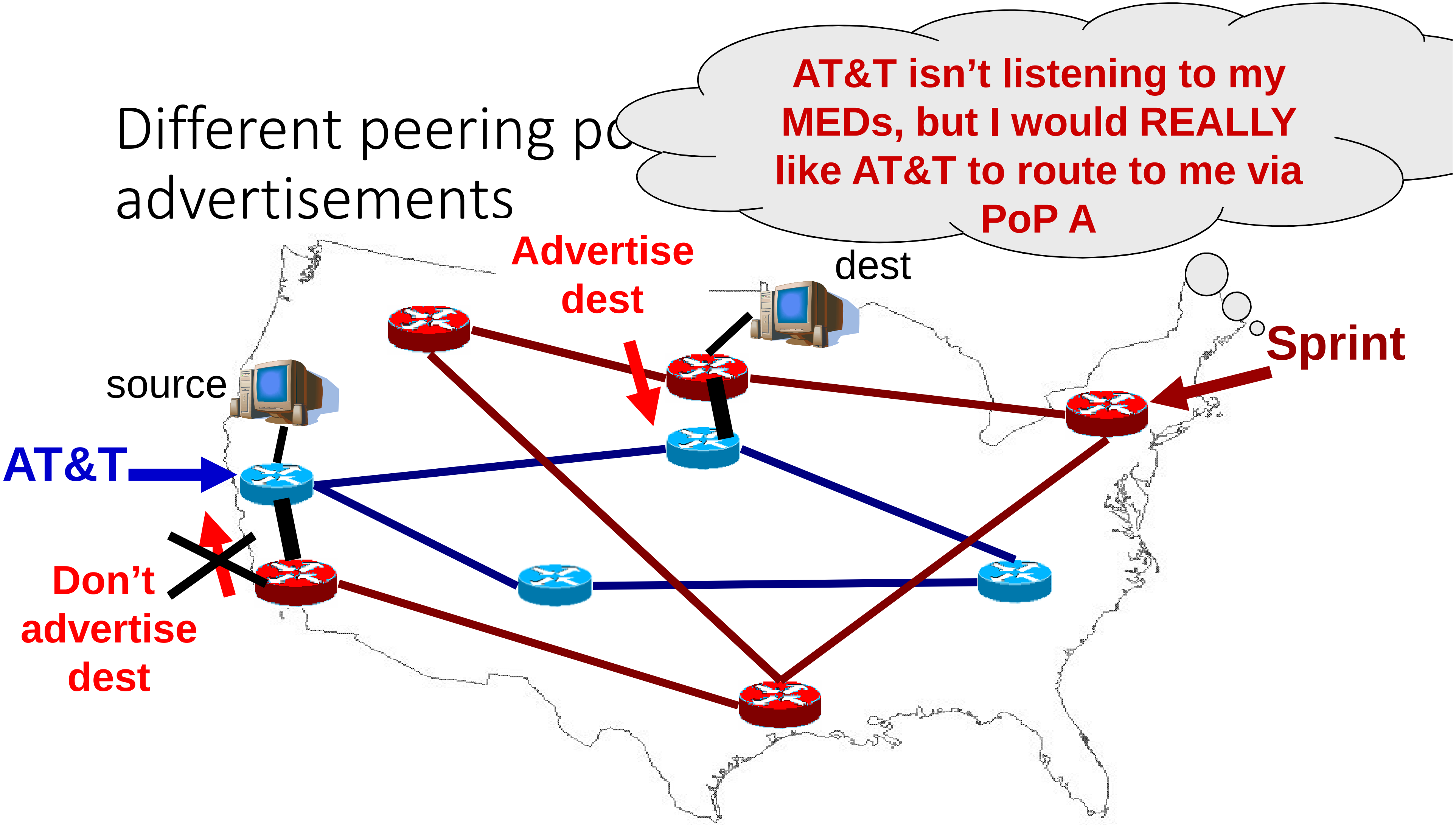
Example: Using MED t
ingresses





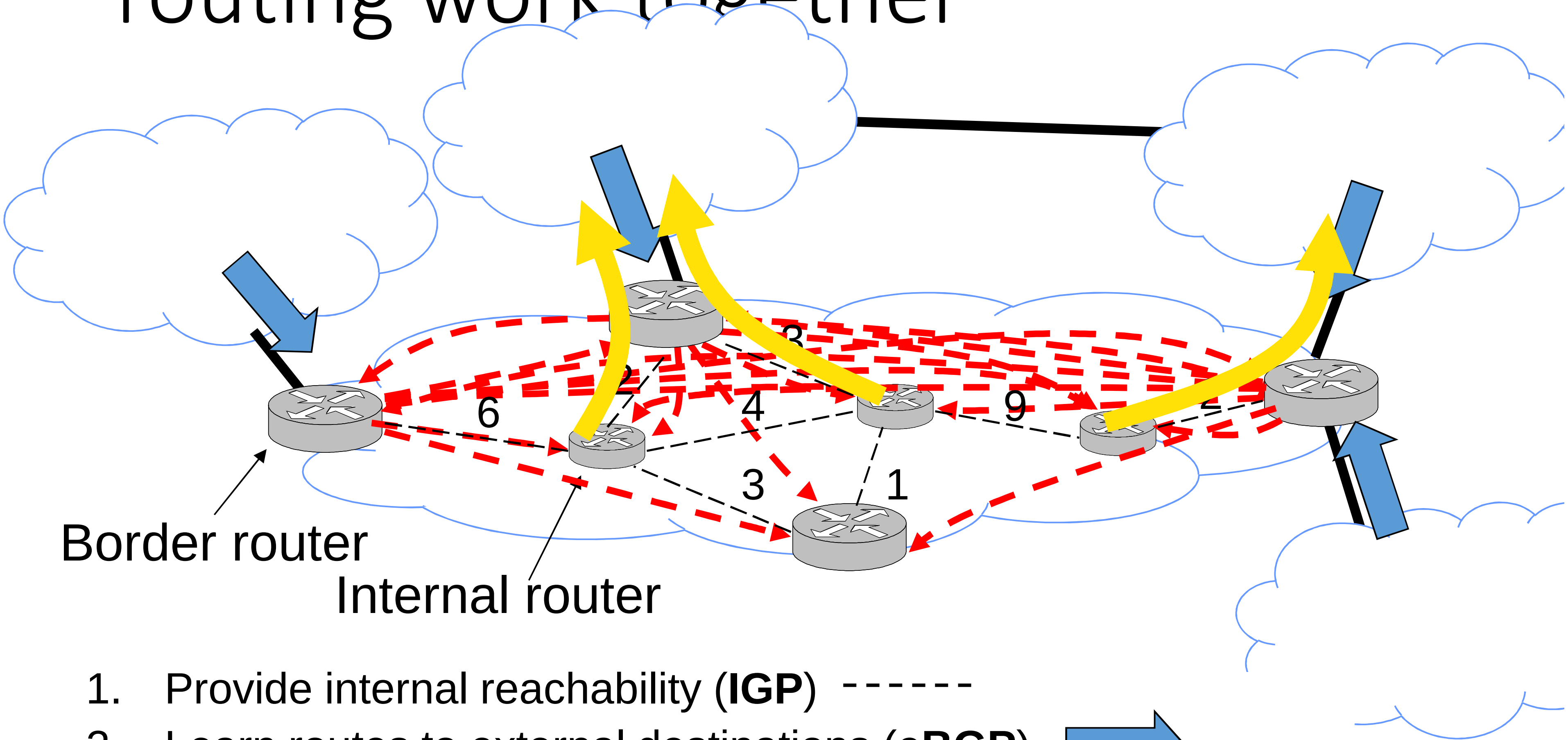
- MED: “multi-exit discriminator”
  - tell neighboring ISP which ingress peering points I prefer
  - Local ISP can choose to filter MED on import

Different peering po
advertisements



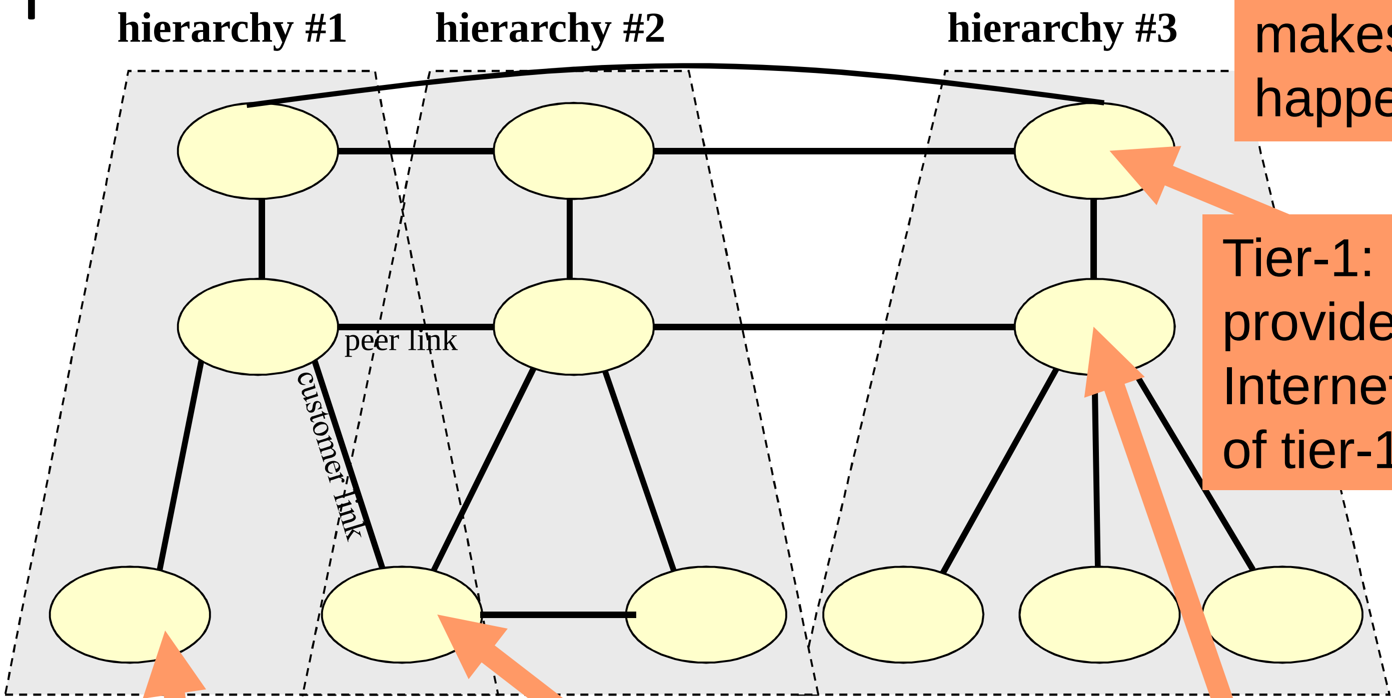
- Sprint can trick AT&T into routing over longer distance!
- Consistent export: make sure your neighbor is advertising the same set of prefixes at all peering points
- ISPs sometimes sign SLAs with consistent export clause

How inter- and intra- domain routing work together



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

Policies between ISPs: Types of ASes



Tier-1s must be connected in a full mesh (Why? Who makes sure that happens?)

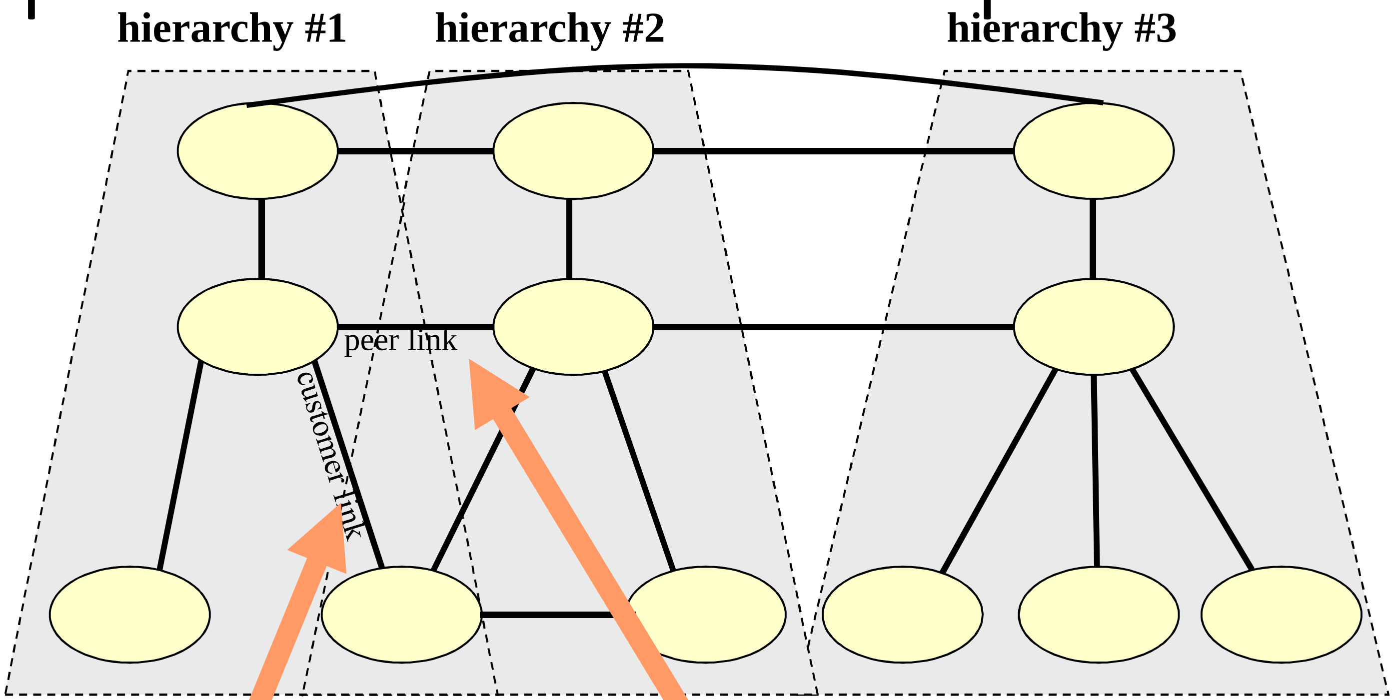
Tier-1: ISP with no providers (core of Internet is clique of tier-1s)

Stub: ISP with no customers

Multihomed: ISP with more than one provider

Transit: ISP that forward traffic between other ISPs

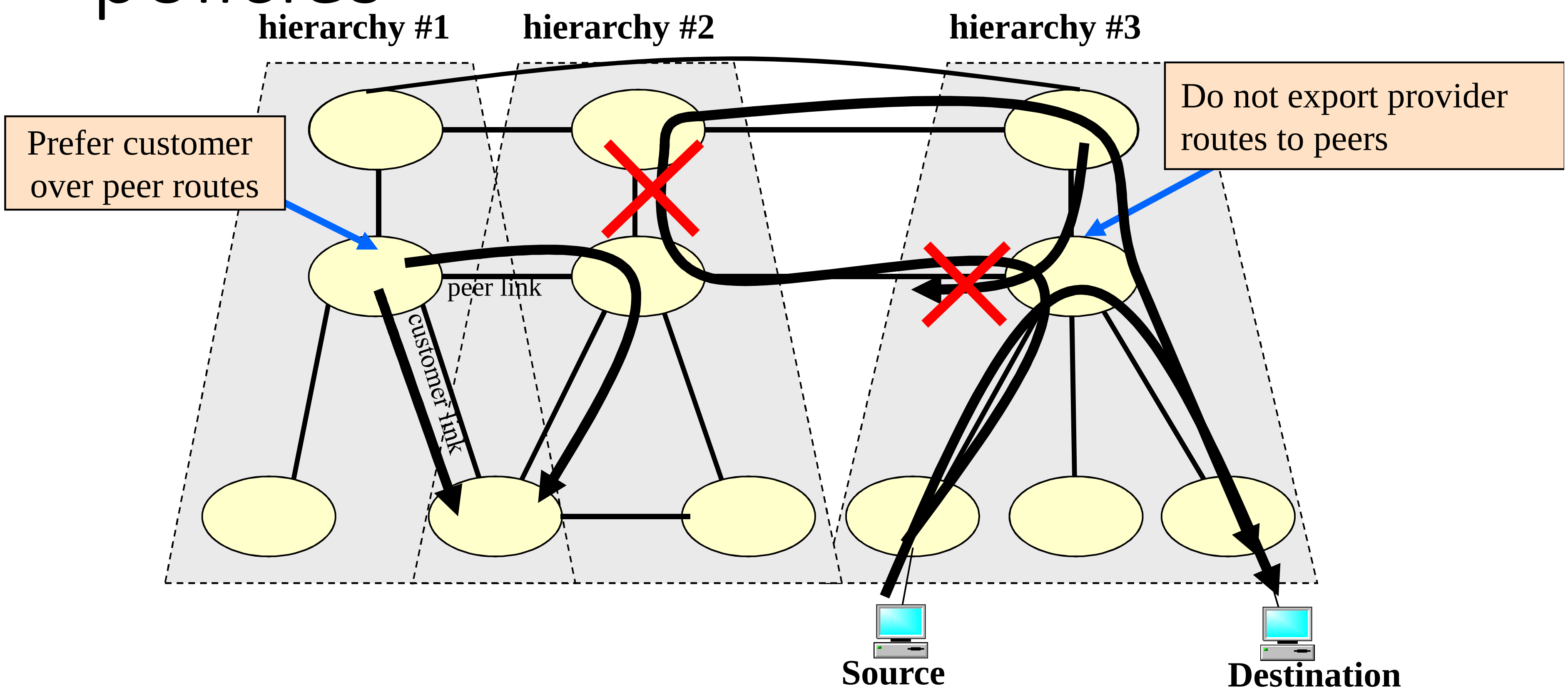
Policies between ISPs: Types of AS relationships



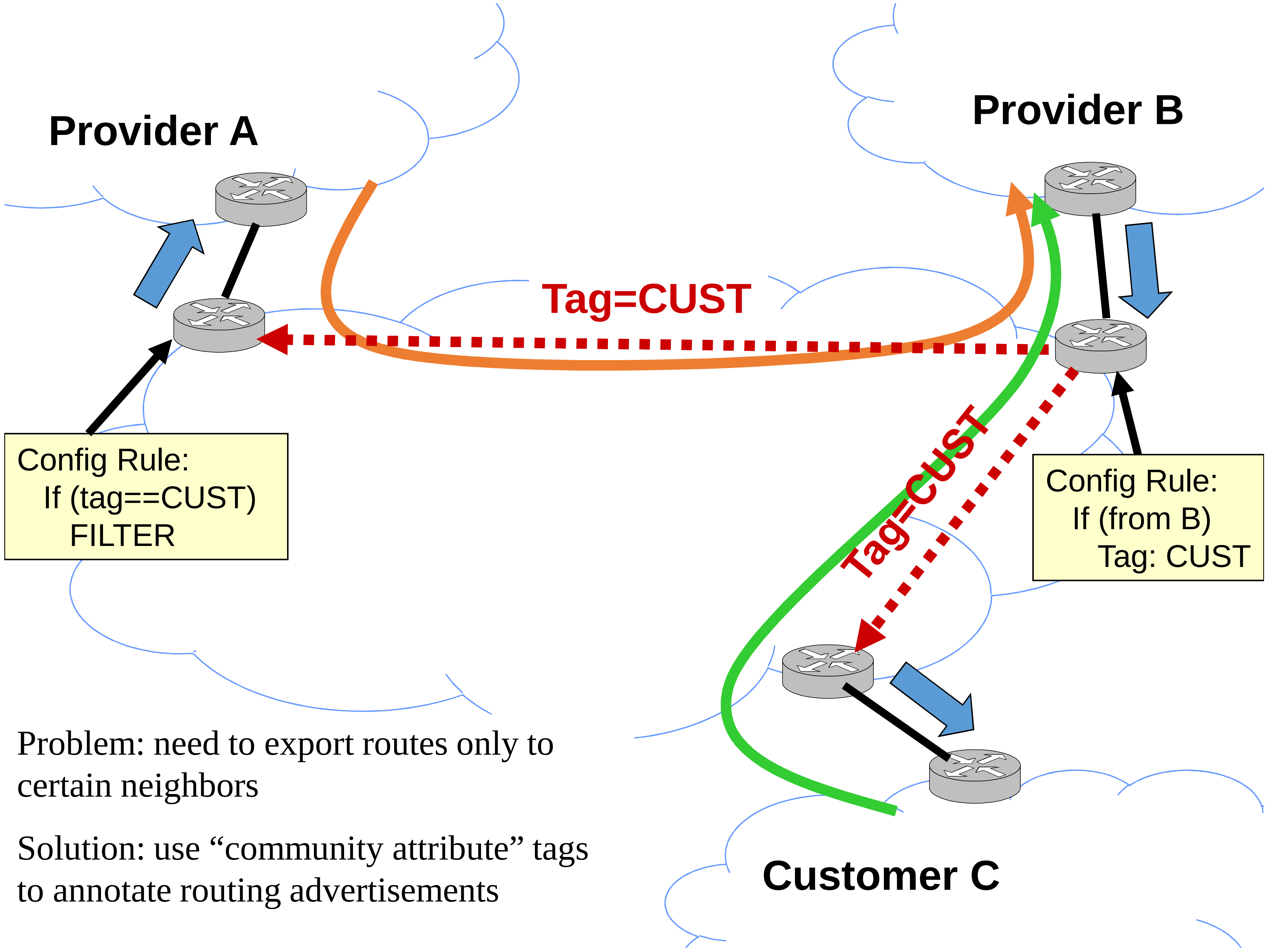
Provider-customer: customer pays provider money to transit traffic

Peer link: ISPs form link out of mutual benefit, typically no money is exchanged

AS relationships influence routing policies



- Example policies: peer, provider/customer
- Also trust issues, security, scalability, traffic engineering

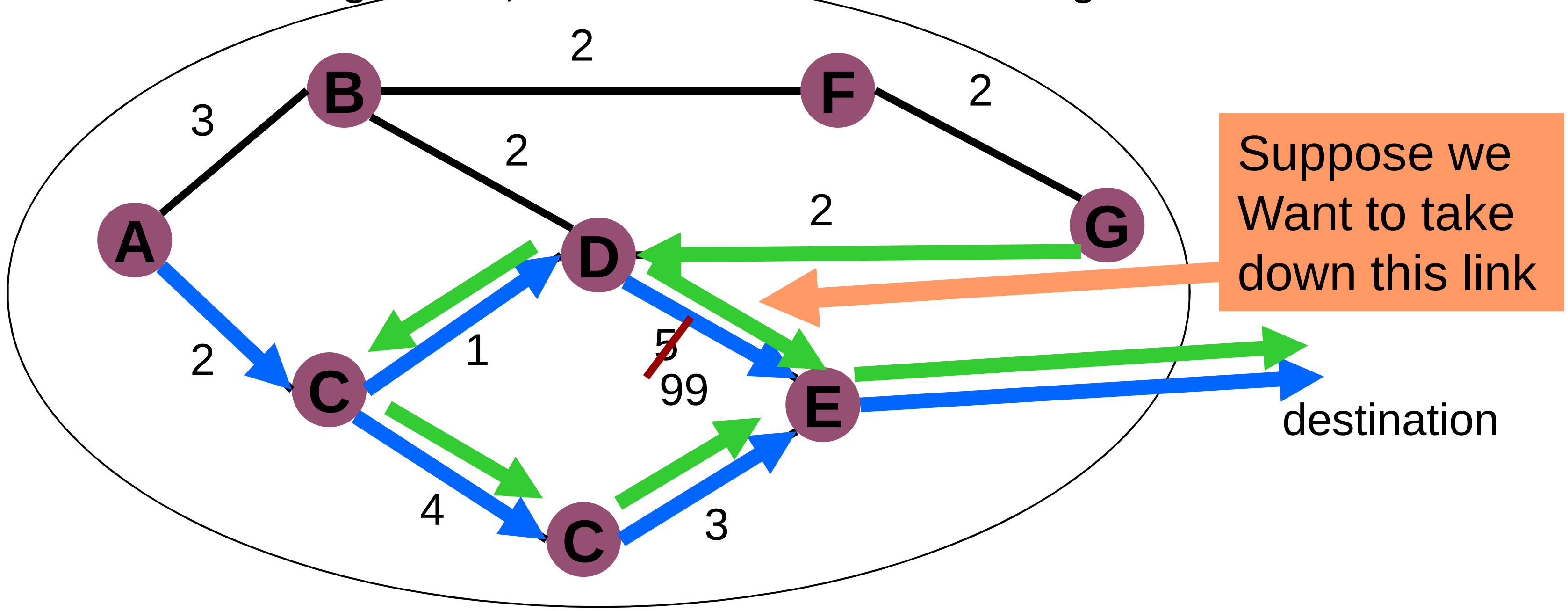


Problem: need to export routes only to certain neighbors

Solution: use “community attribute” tags to annotate routing advertisements

“Costing out” of equipment

- Increase cost of link to high value
  - Triggers immediate flooding of LSAs
- Leads to new shortest paths avoiding the link
  - While the link still exists to forward during convergence
- Then, can safely disconnect the link
  - New flooding of LSAs, but no influence on forwarding



Today

- Addressing
- BGP
  - today: context and key ideas
  - next lecture: details and issues

Addressing Goal: Scalable Routing

- State: Small forwarding tables at routers
  - Much less than the number of hosts
- Churn: Limited rate of change in routing tables
  - Traffic, inconsistencies, complexity

Ability to aggregate addresses is crucial for both

(one entry to *summarize* many addresses)

Aggregation only 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

Hence, IP Addressing: Hierarchical

- Hierarchical address structure
- Hierarchical address allocation
- Hierarchical addresses and topology

IP Addresses (IPv4)

- Unique 32-bit number associated with a host
- Represented with the ***dotted-quad*** notation, e.g., **12.34.158.5**:

12	**34**	**158**	**5**
00001100	00100010	10011110	00000101

Examples

- What address is this? 80.19.240.51

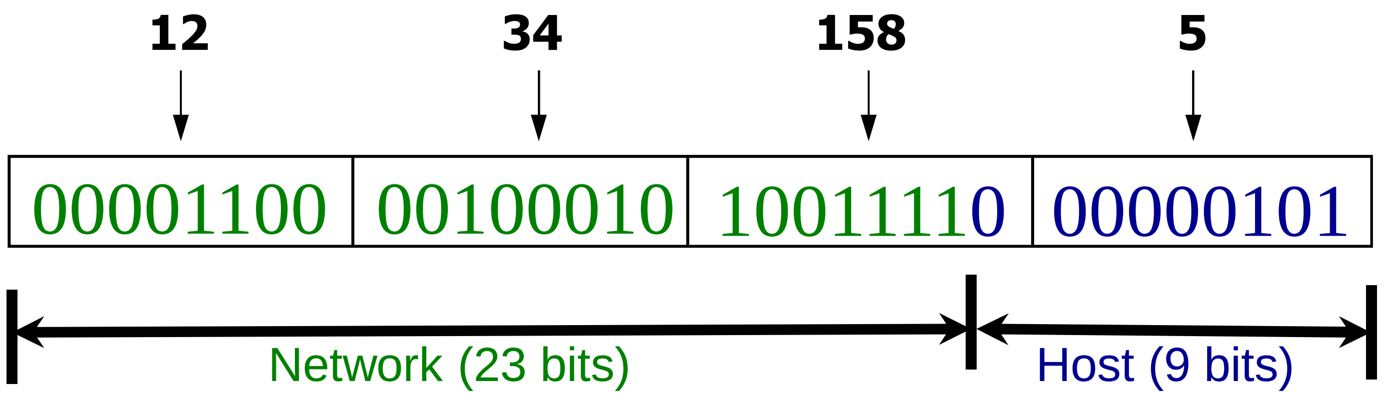
01010000	00010011	11110000	00110011

- How would you represent 68.115.183.7?

01000100	01110011	10110111	00000111

Hierarchy in IP Addressing

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



- Interdomain routing operates on the network prefix
- Notation and terminology: 12.34.158.0/23 represents a "slash 23" network with a 23 bit prefix and 2^9 host addresses

History of Internet Addressing

- Always dotted-quad notation
- Always network/host address split
- But nature of that split has changed over time

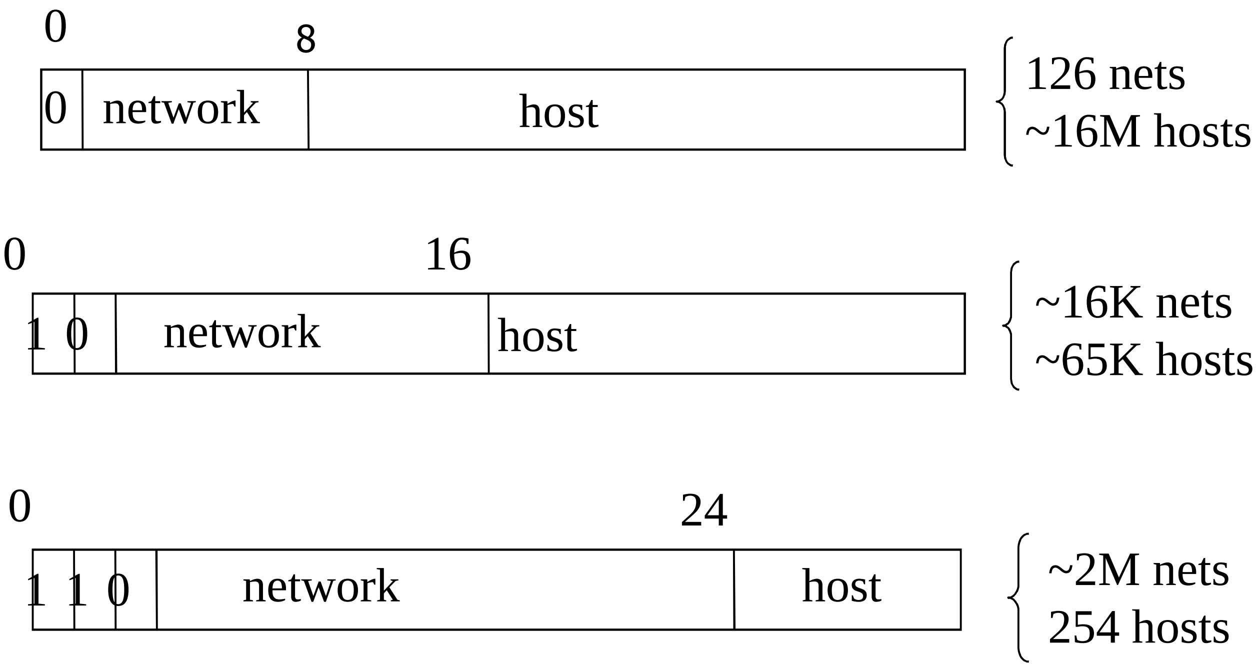
Original Internet Addresses

- First eight bits: network address (/8)
- Last 24 bits: host address

Assumed 256 networks were more than enough!

Next Design: “Classful” Addressing

- Three main classes
  - Class A
  - Class B
  - Class C



Problem: Networks only come in three sizes!

Today’s Addressing: CIDR

- CIDR = Classless Interdomain Routing
- Idea: Flexible division between network and host addresses
- Motivation: offer a better tradeoff between size of the routing table and efficient use of the IP address space

CIDR (example)

- Suppose a network has fifty computers
  - allocate 6 bits for host addresses (since $2^5 < 50 < 2^6$)
  - remaining 32 - 6 = 26 bits as network prefix
  - E.g., 128.23.9/26 is a "slash 26" network

- Flexible boundary between network and host bits means the boundary must be explicitly specified with the network address
  - informally, "slash 26" → 128.23.9/26
  - formally, represent length of prefix with a 32-bit mask: 256.256.256.192 where all network prefix bits set to "1" and host suffix bits to "0"

Classful vs. Classless addresses

- Example: an organization needs 500 addresses.
  - A single class C address not enough (254 hosts).
  - Instead a class B address is allocated. (~65K hosts)
  - That's overkill, a huge waste!

- CIDR allows an arbitrary prefix-suffix boundary
  - Hence, organization allocated a single /23 address (equivalent of 2 class C's)

- Maximum waste: 50%

Hence, IP Addressing: 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 (e.g., ARIN), which give blocks to
  - *ARIN → American Registry for Internet Numbers*

- Large institutions (ISPs), which give addresses to…

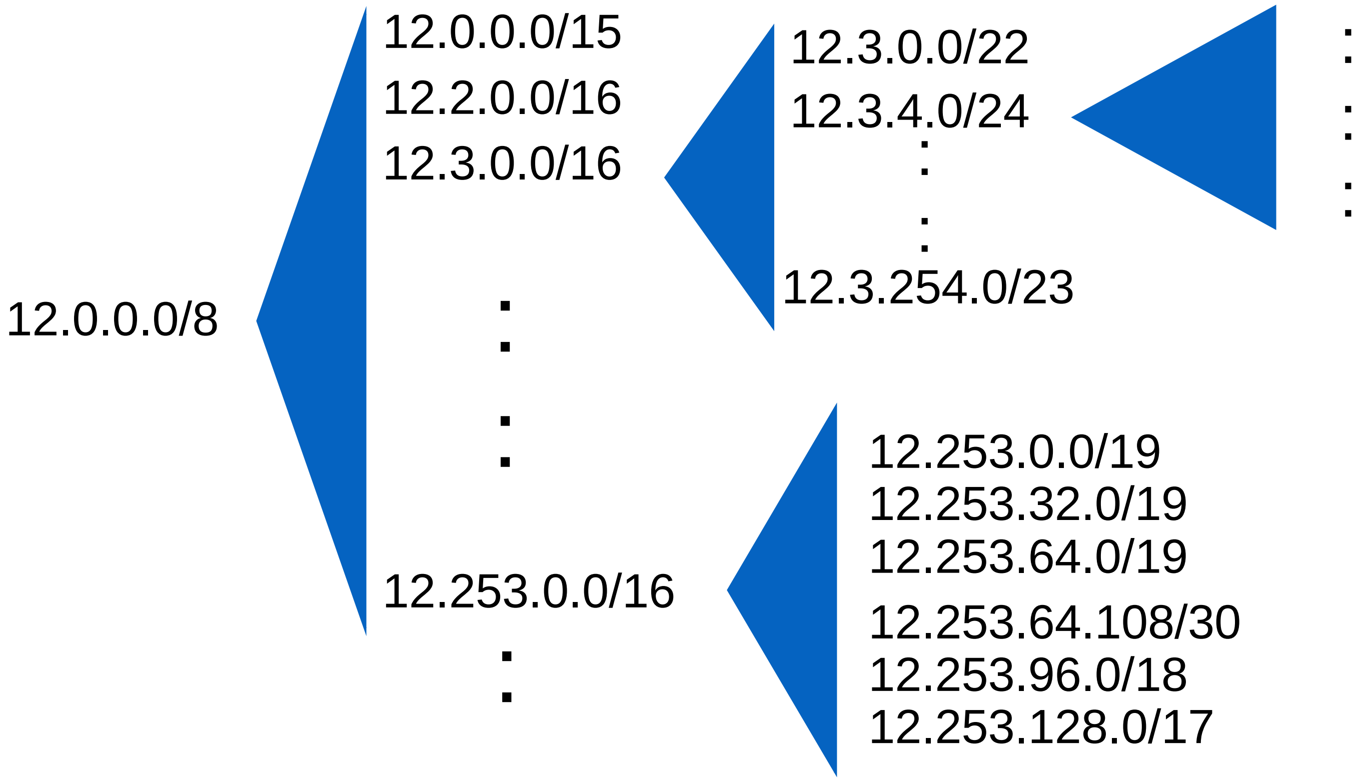
- Individuals and smaller institutions

- FAKE Example:

  ICANN → ARIN → AT&T → UCB → EECS

CIDR: Addresses allocated in contiguous prefix chunks

Recursively break down chunks as get closer to host



FAKE Example in More Detail

- ICANN gives ARIN several /8s
- ARIN gives AT&T one /8, **12.0/8**
  - Network Prefix**: 00001100**
- AT&T gives UCB a /16, **12.197/16**
  - Network Prefix**: 0000110011000101**
- UCB gives EECS a /24, **12.197.45/24**
  - Network Prefix**: 000011001100010100101101**
- EECS gives me a specific address **12.197.45.23**
  - Address: 00001100110001010010110100010111

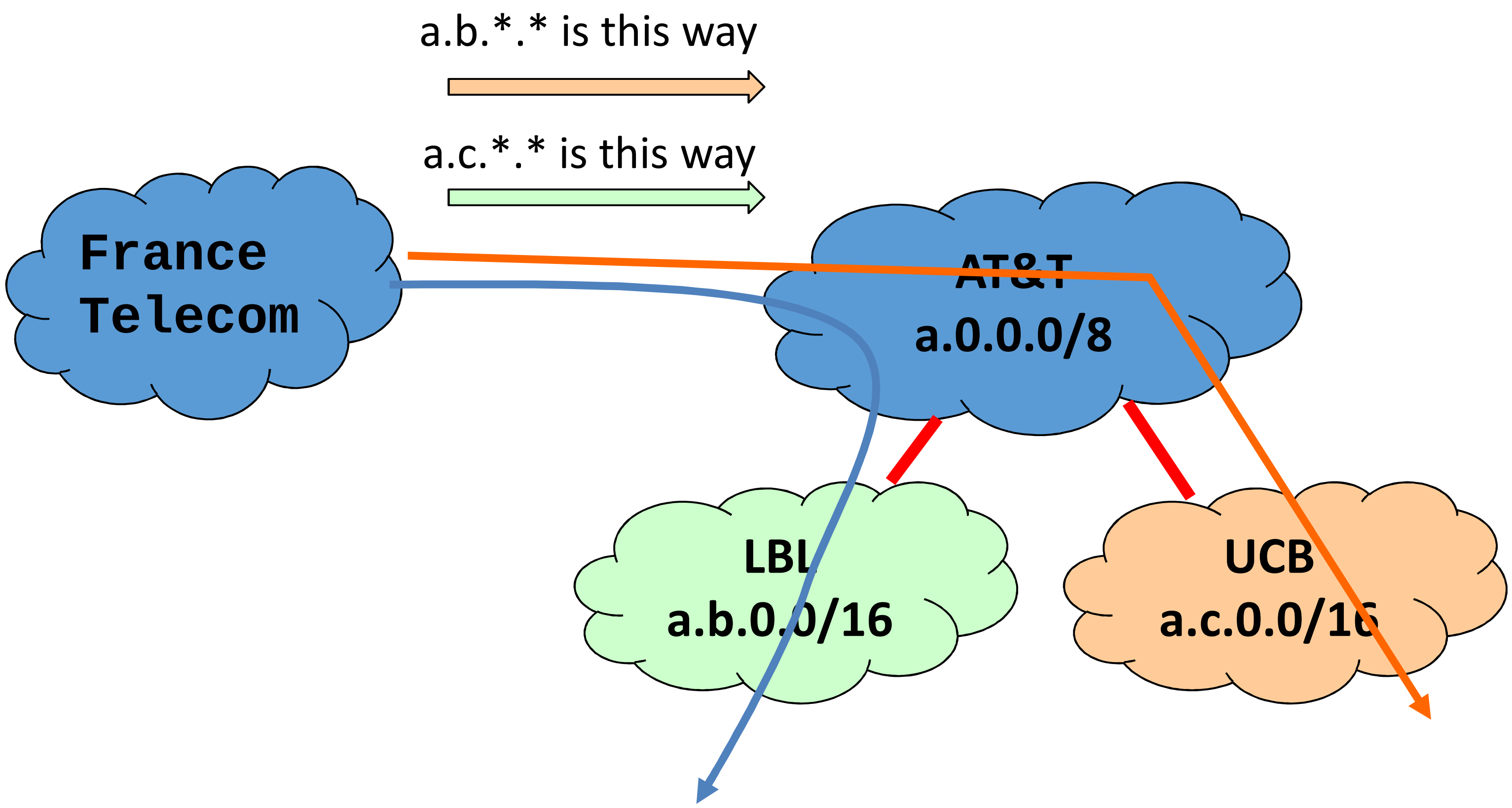
Hence, IP Addressing: Hierarchical

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

IP addressing → scalable routing?

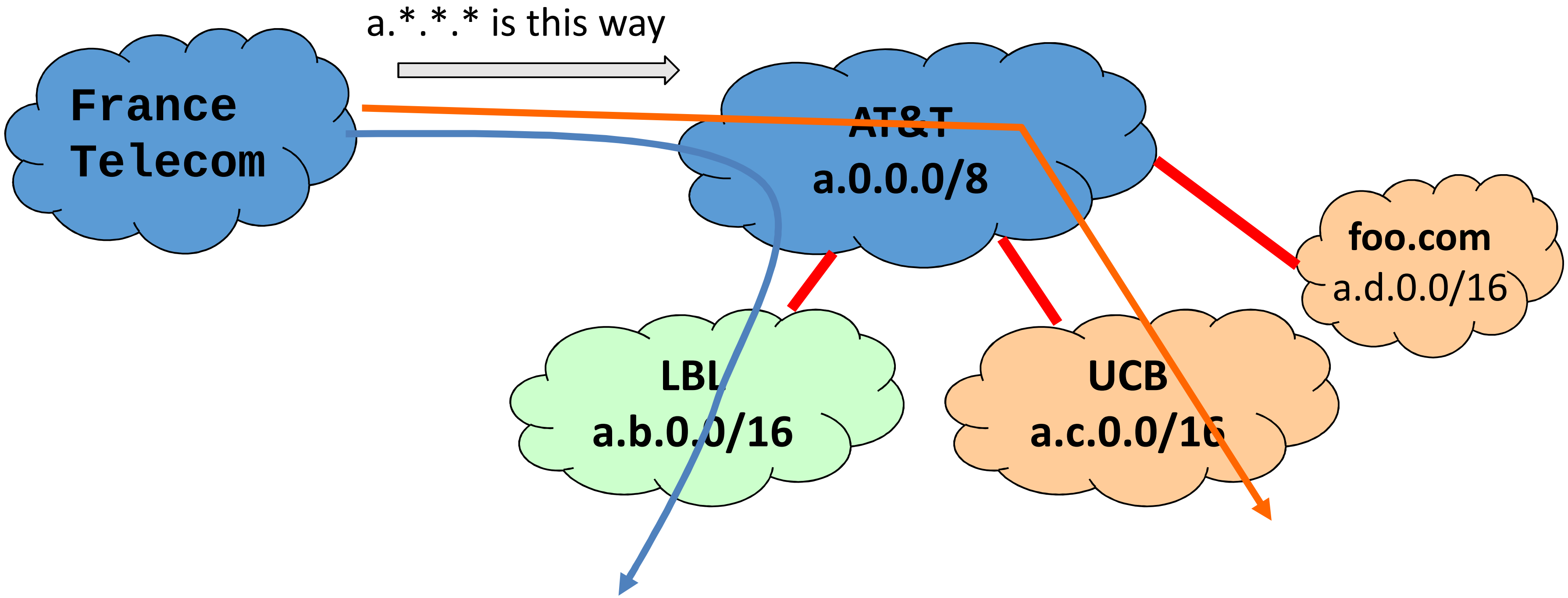
- Hierarchical address allocation helps routing scalability if allocation matches topological hierarchy

IP addressing → scalable routing?



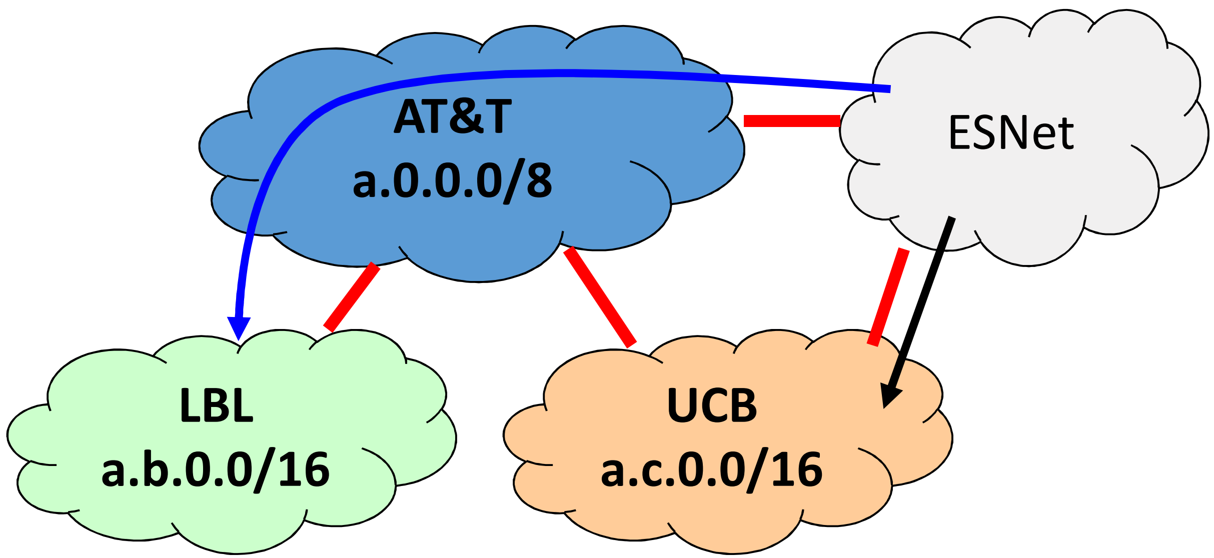
IP addressing → scalable routing?

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.*.*



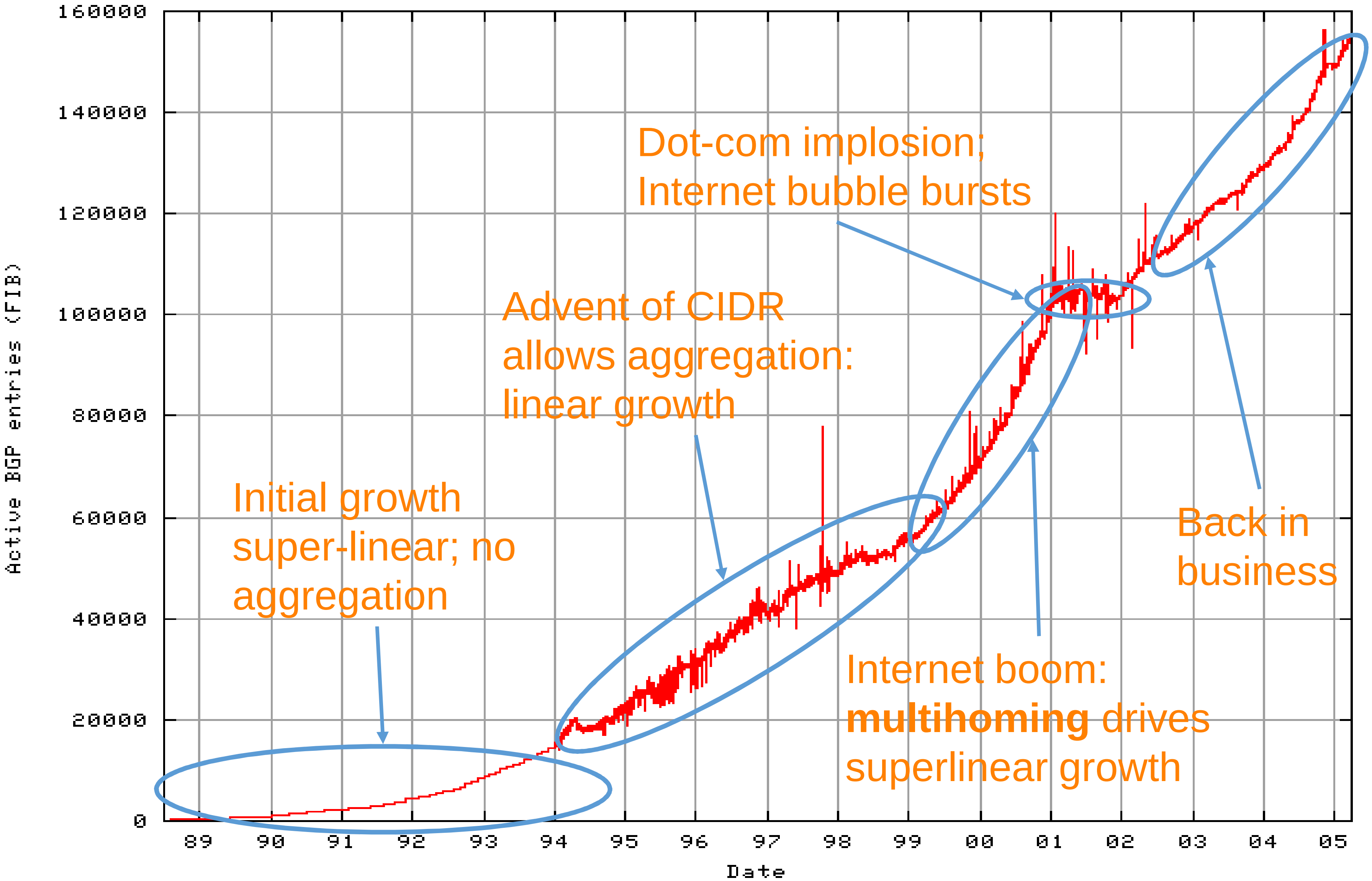
IP addressing → scalable routing?

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

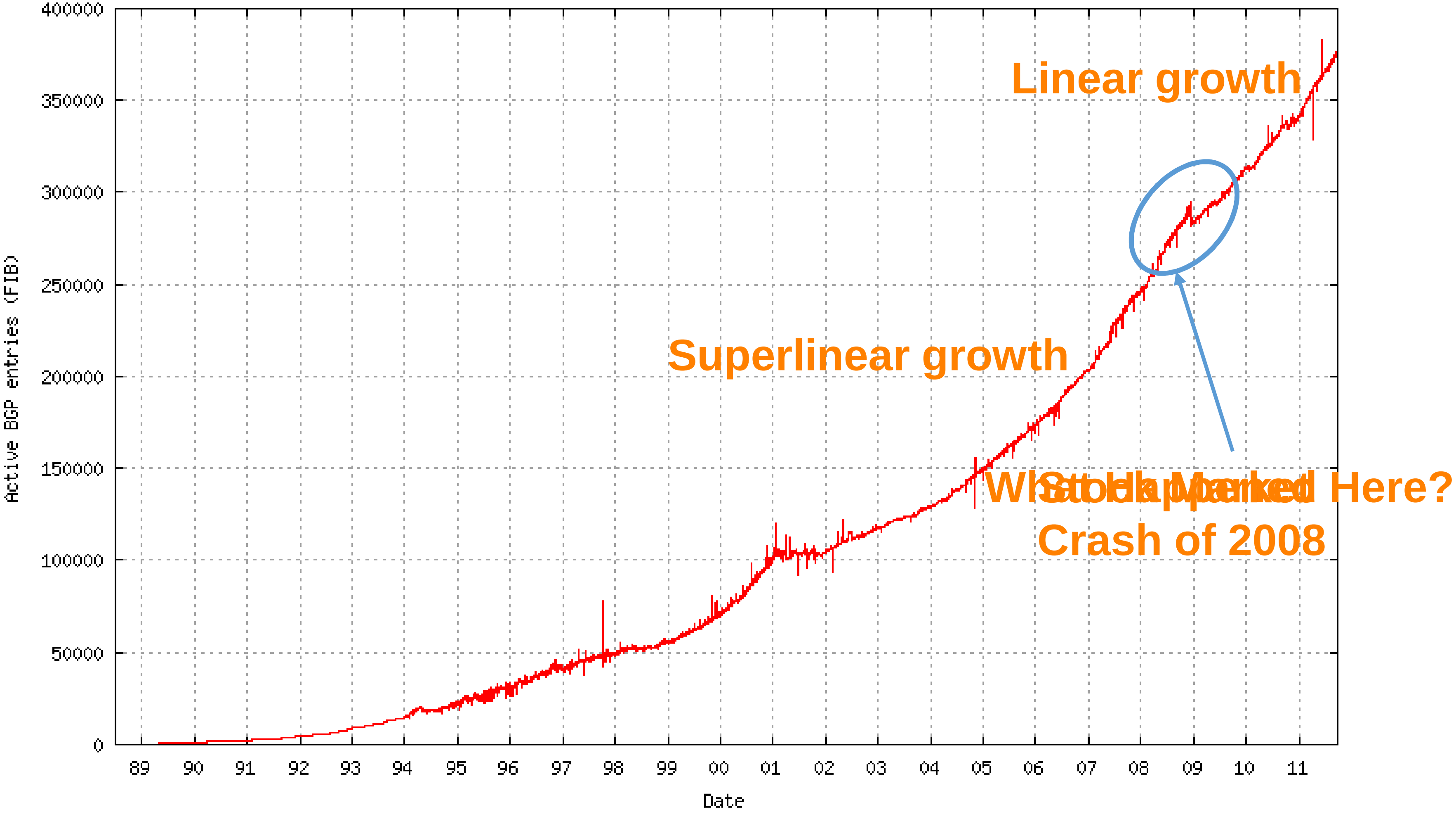
- Problem: may not be able to aggregate addresses for "multi-homed" networks

- Two competing forces in scalable routing
  - aggregation reduces number of routing entries
  - multi-homing increases number of entries

Growth in Routed Prefixes (1989-2005)



Same Table, Extended to Present



Summary of Addressing

- **Hierarchical** addressing
  - Critical for **scalable** system
  - Don't require everyone to know everyone else
  - Reduces amount of updating when something changes
- **Non-uniform** hierarchy
  - Useful for heterogeneous networks of different sizes
  - Class-based addressing was far too coarse
  - Classless InterDomain Routing (CIDR) more flexible
- A later lecture: impact of CIDR on router designs

Outline

- Addressing

- Border Gateway Protocol (BGP)
  - today: context and key ideas
  - next lecture: details and issues

BGP (Today)

- The role of policy
  - what we mean by it
  - why we need it
- Overall approach
  - four non-trivial changes to DV
  - how policy is implemented (detail-free version)

Administrative structure shapes Interdomain routing

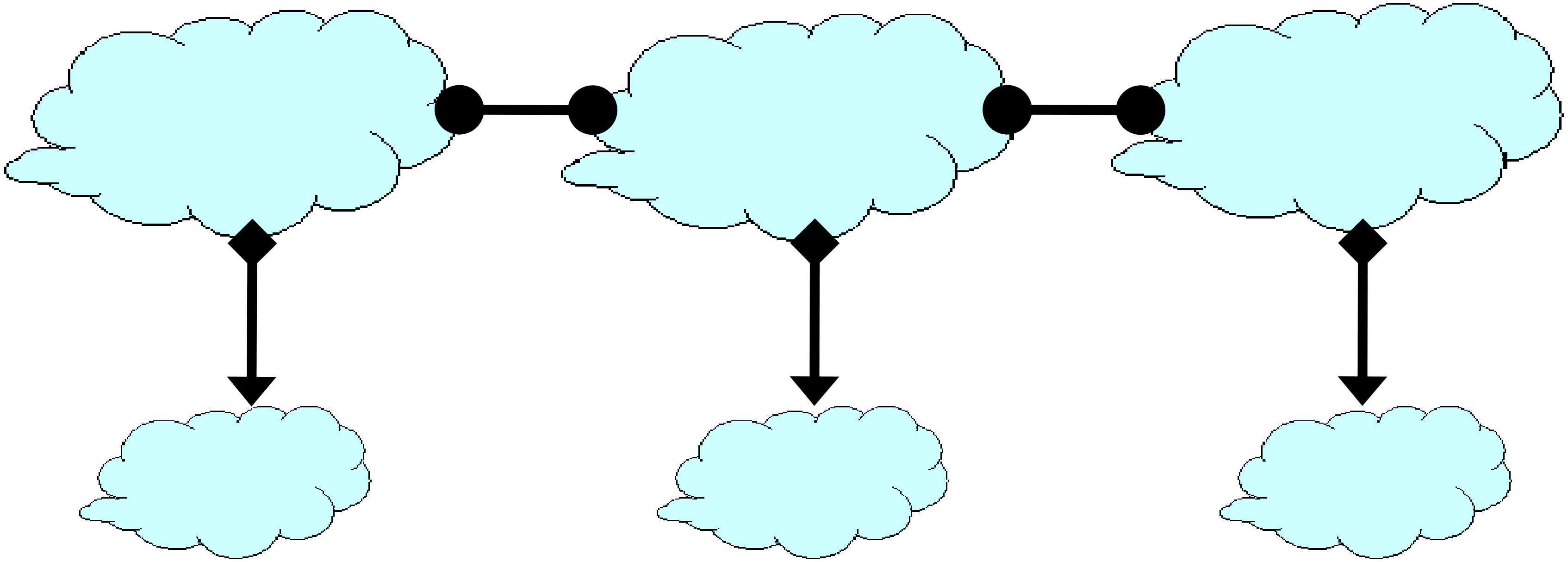
- ASes want freedom to pick routes based on policy
- ASes want autonomy
- ASes want privacy

Topology and policy is shaped by the business relationships between ASes

- 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

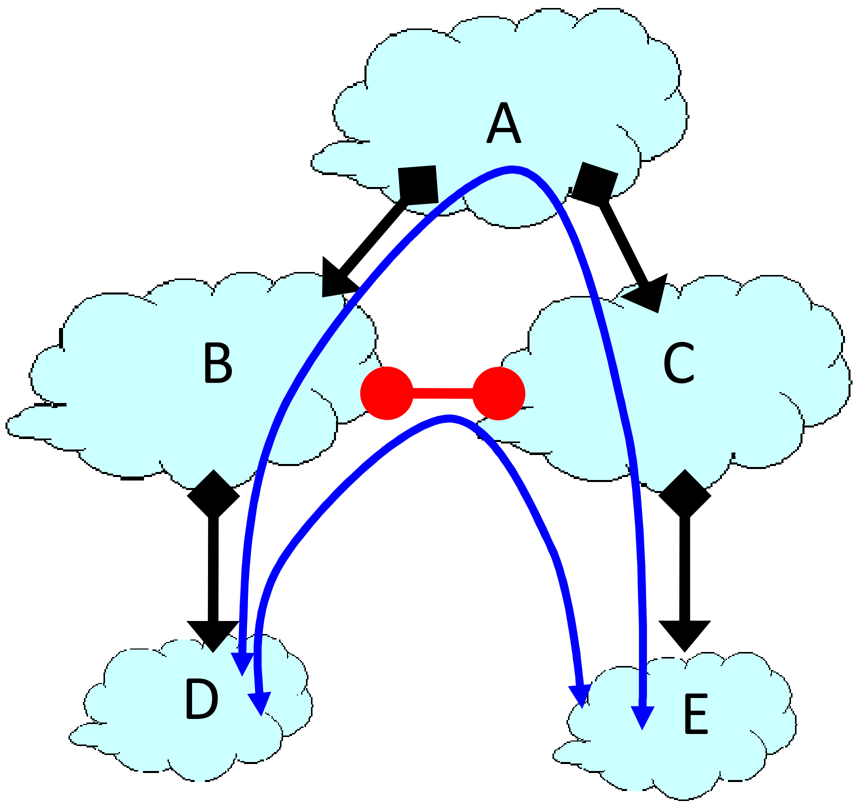
provider ◆⟶ customer

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

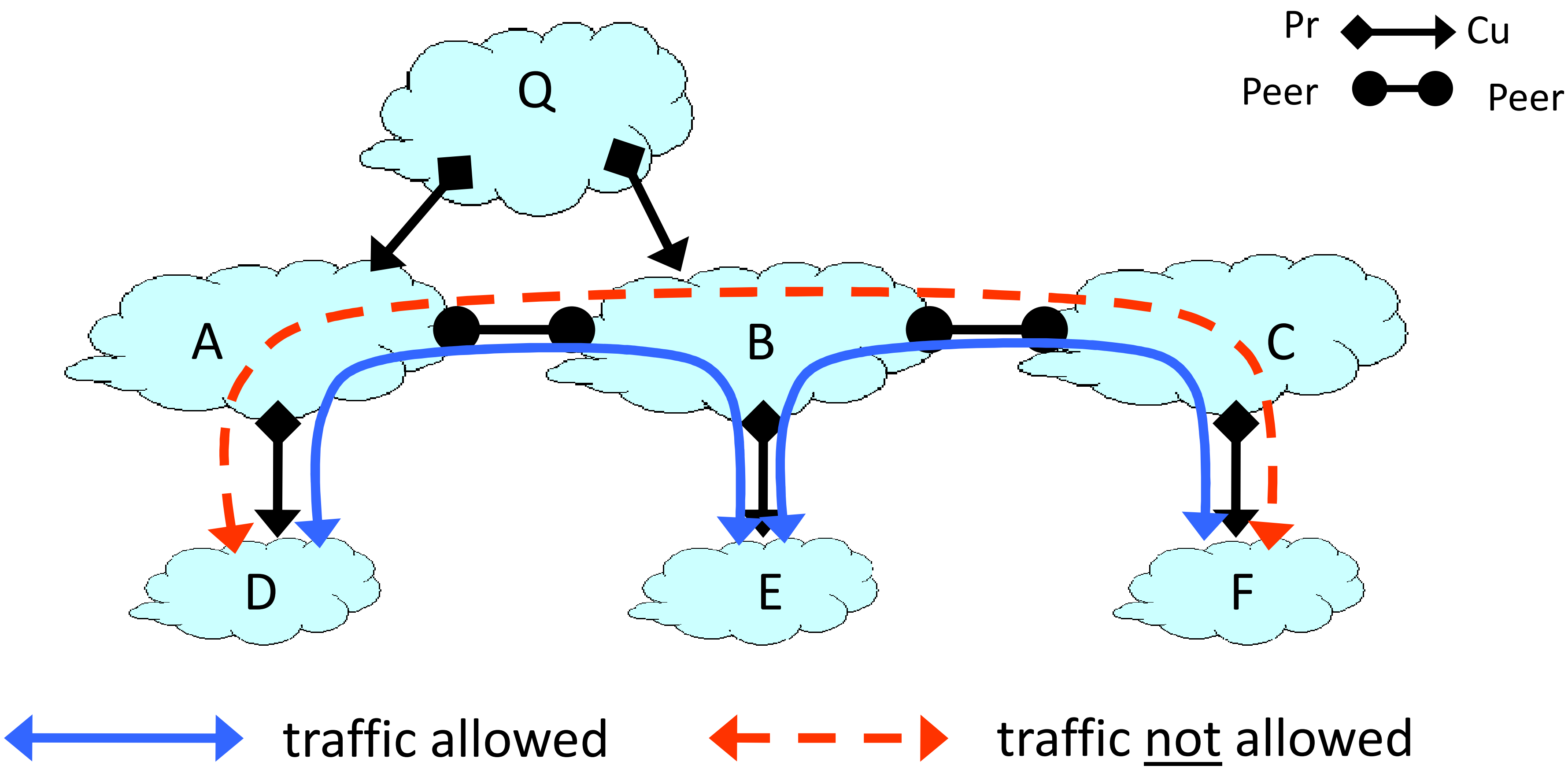
provider ⟶ customer

peer —— peer

Business Implications

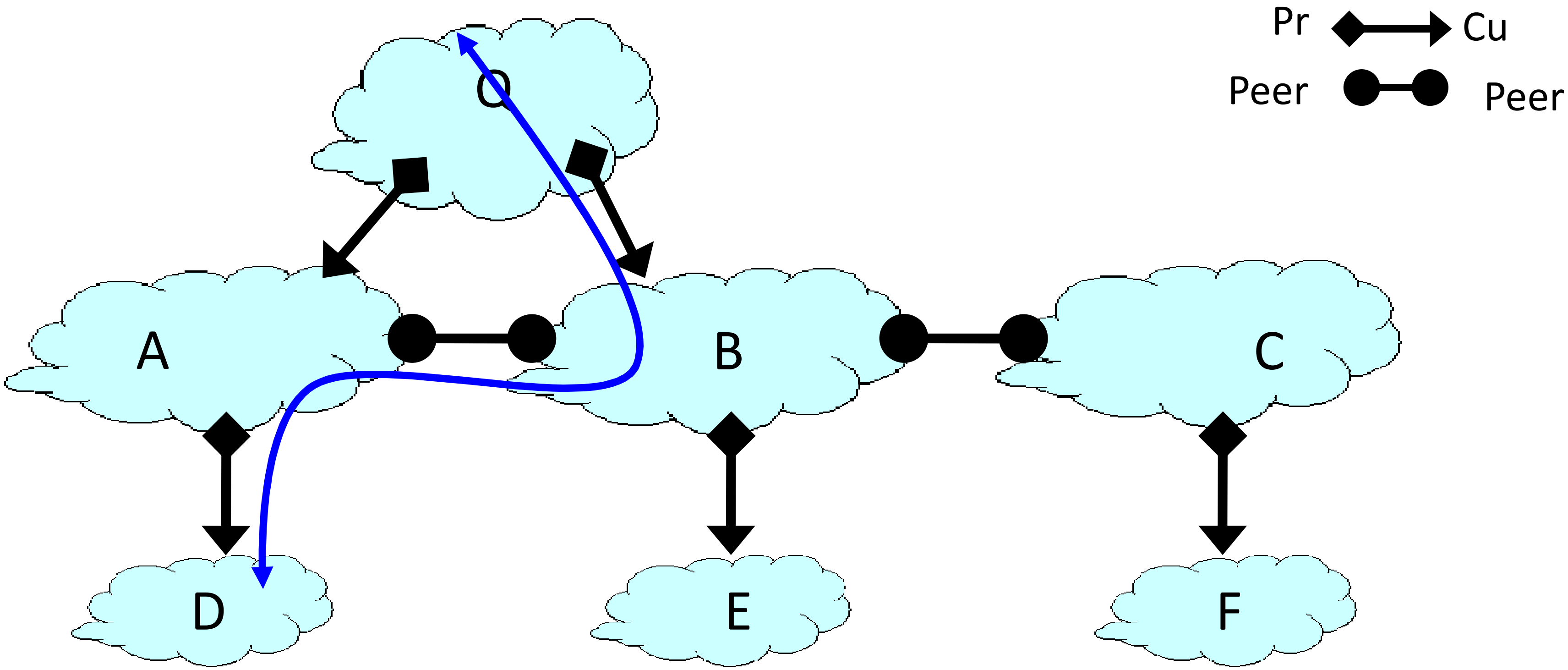
- Customers pay provider
- Peers don't pay each other

Routing Follows the Money!



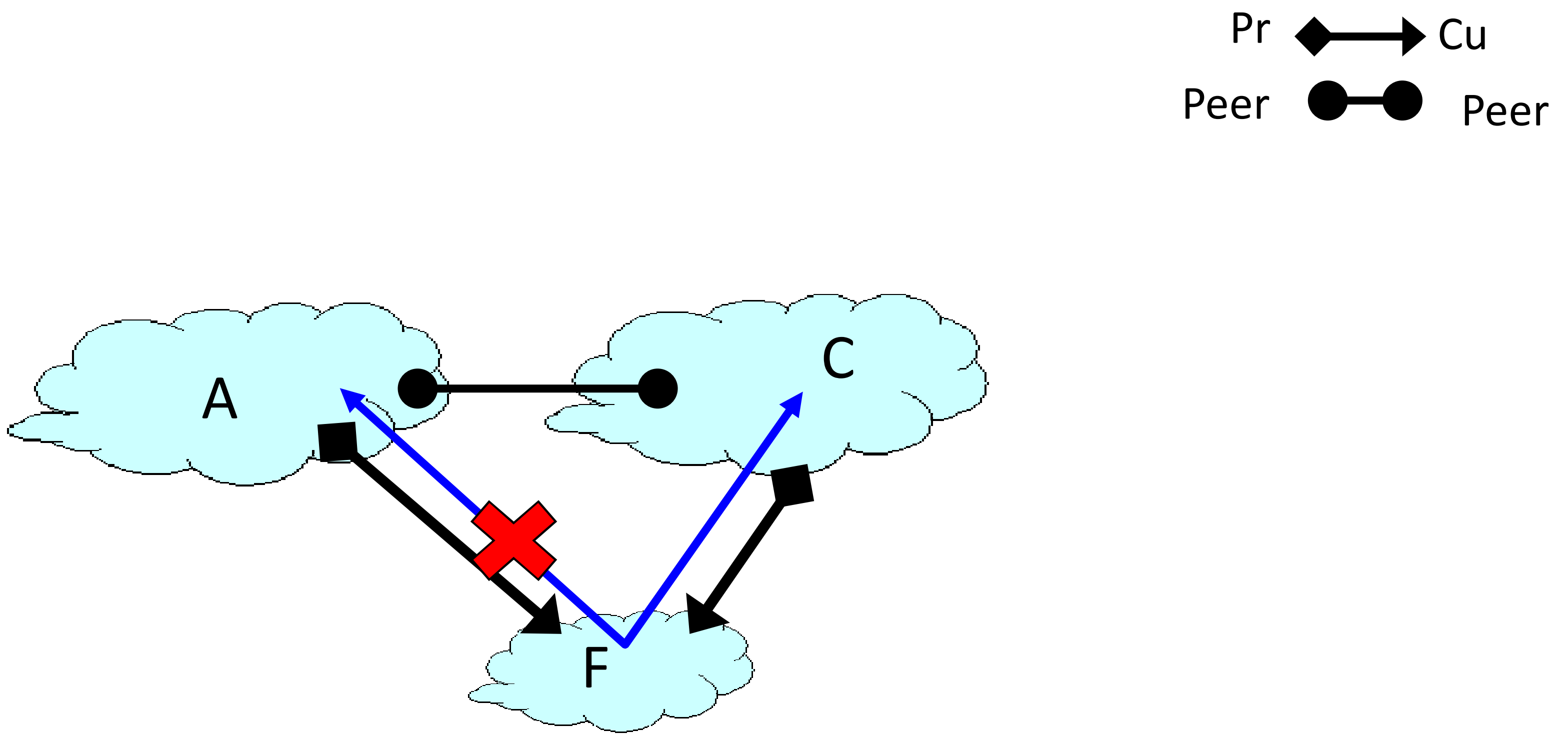
- ASes provide "transit" between their customers
- Peers do not provide transit between other peers

Routing Follows the Money!



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

Routing Follows the Money!



- Routes are “valley free” (will return to this later)

In Short

- AS topology reflects business relationships between Ases
- Business relationships between ASes impact which routes are acceptable
- BGP Policy: Protocol design that allows ASes to control which routes are used
- Next lecture: more formal analysis of the impact of policy on reachability and route stability

BGP (Today)

- The role of policy
  - what we mean by it
  - why we need it
- Overall approach
  - four non-trivial changes to DV
  - how policy is implemented (detail-free version)

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: 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!

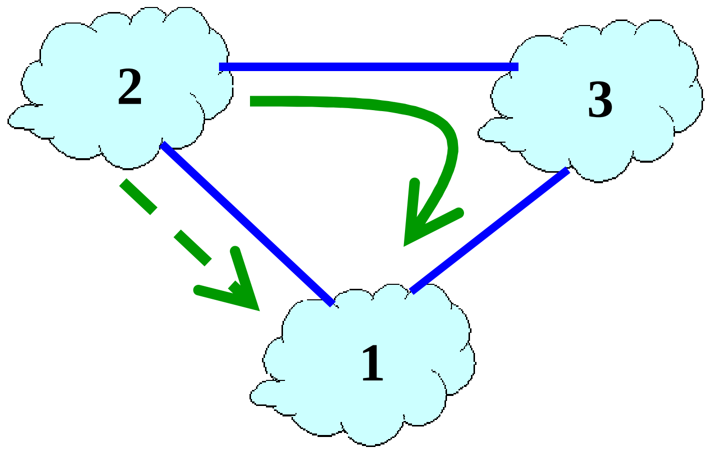
BGP inspired by Distance Vector

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

Differences between BGP and DV
(1) not picking shortest path routes

- BGP selects the best route based on policy, not shortest distance (least cost)

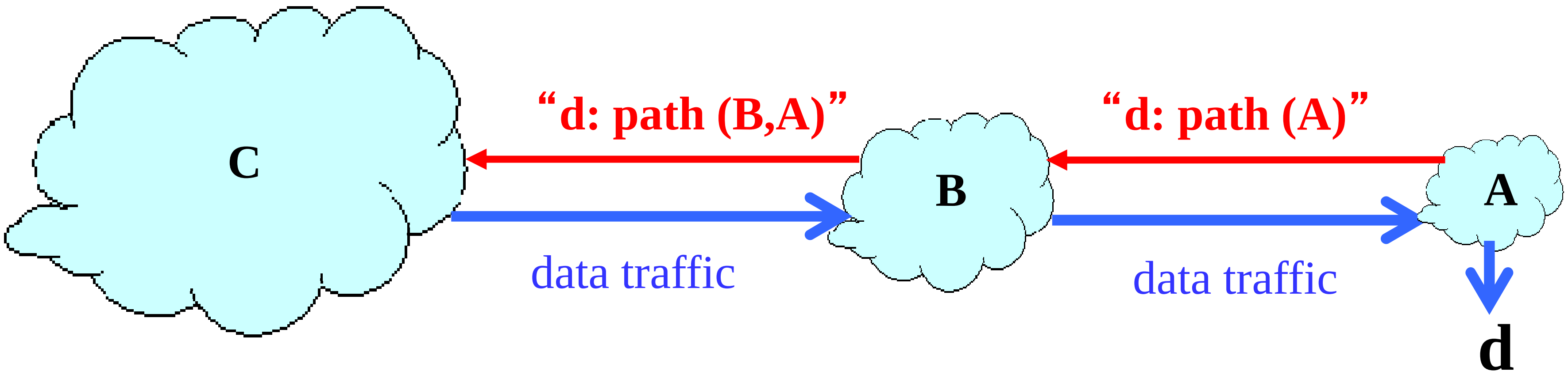
Node 2 may prefer “2, 3, 1” over “2, 1”



- How do we avoid loops?

Differences between BGP and DV
(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



Differences between BGP and DV
(2) path-vector routing

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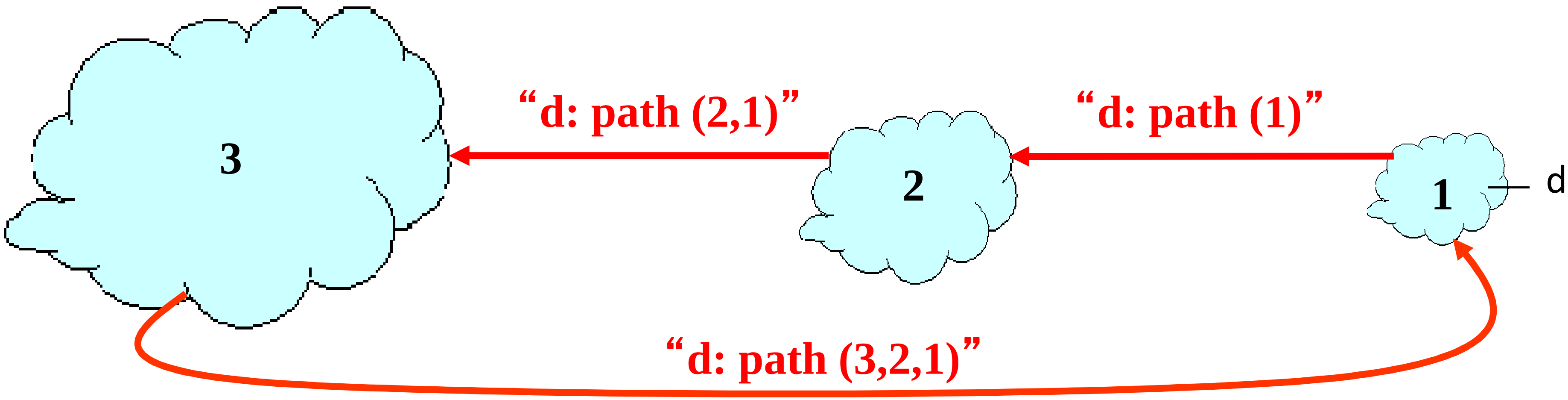
  - Path vector: send the *entire path* for each dest d

- Benefits
  - loop avoidance is easy

Loop Detection w/ 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”
  - E.g., node 1 simply discards the advertisement



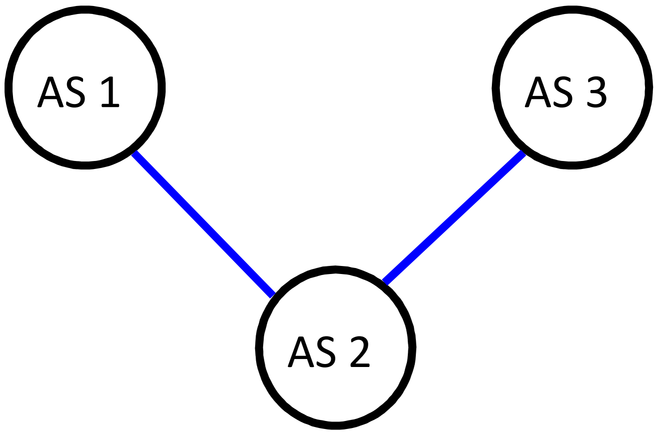
Differences between BGP and DV
(2) path-vector routing

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

- Benefits
  - loop avoidance is easy
  - flexible policies based on entire path

Differences between BGP and DV (3) Selective route advertisement

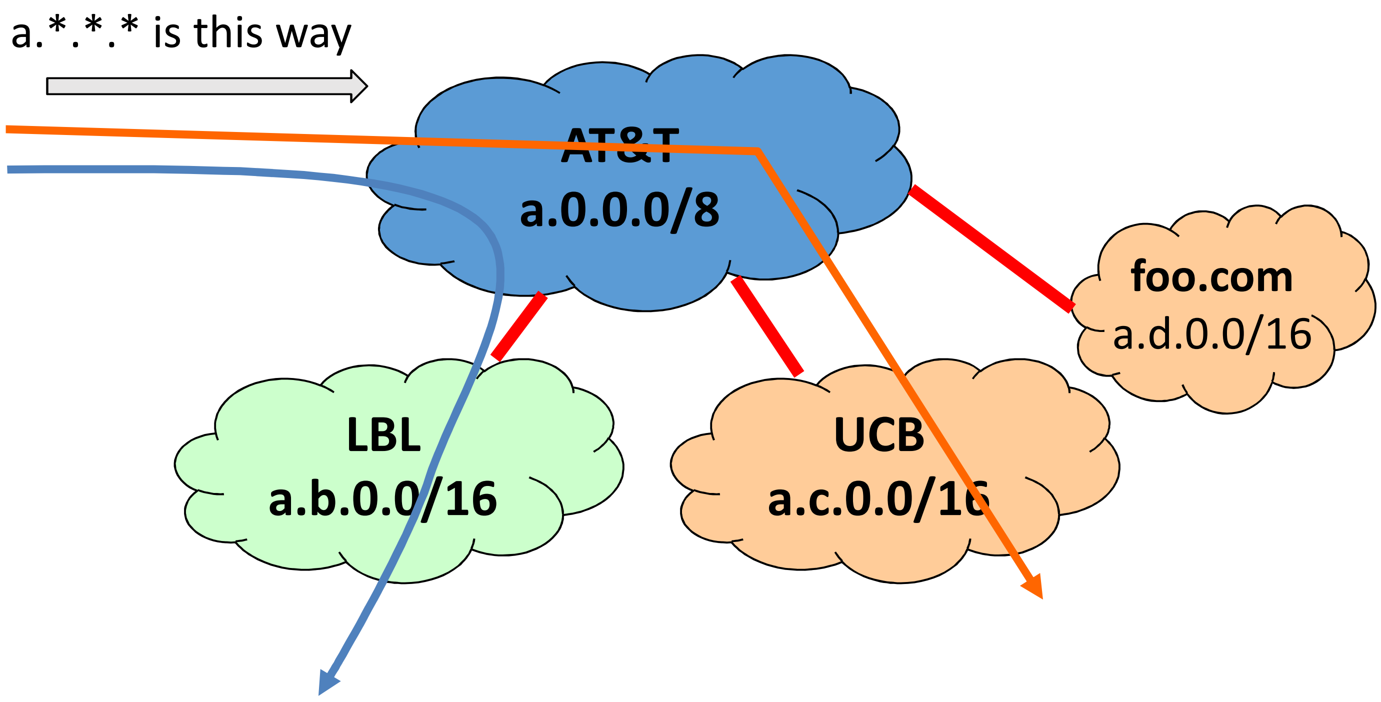
- For policy reasons, an AS may choose not to advertise a route to a destination
- Hence, reachability is not guaranteed even if graph is connected



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

Differences between BGP and DV
(4) BGP may *aggregate* routes

- For scalability, BGP may aggregate routes for different prefixes



BGP (Today)

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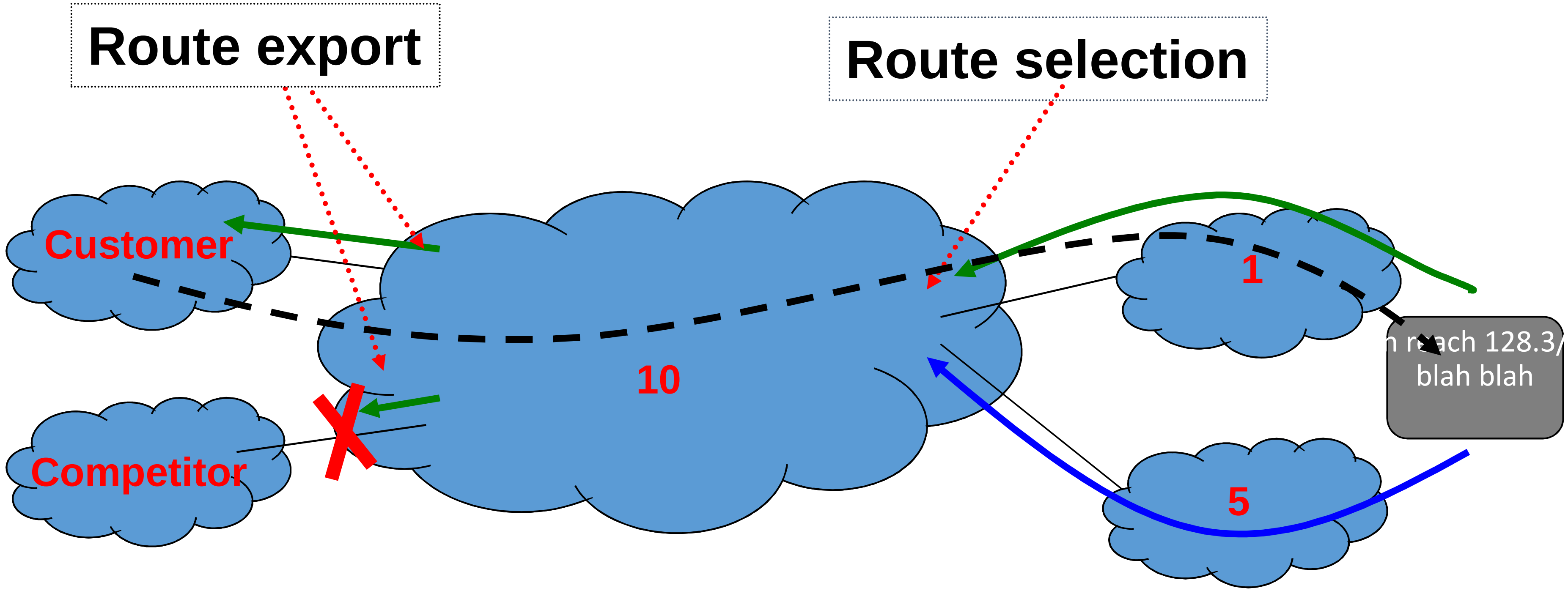
Policy imposed in how routes are selected and exported



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

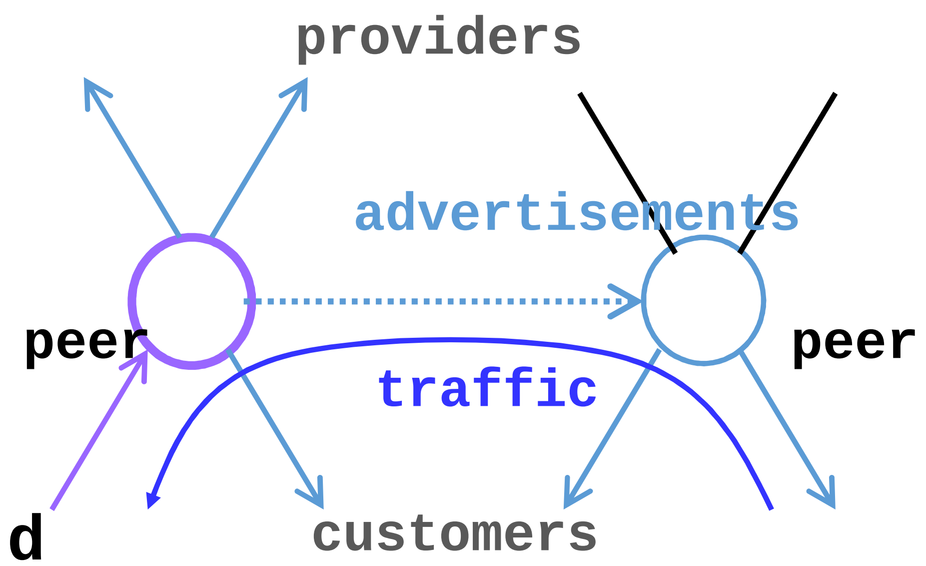
Typical Selection Policy

- In decreasing order of priority
  - make/save money (send to customer > peer > provider)
  - maximize performance (smallest AS path length)
  - minimize use of my network bandwidth (“hot potato”)
  - …
  - …

- BGP uses something called route “attributes” to implement the above (next lecture)

Typical Export: Peer-Peer Case

- Peers exchange traffic between their customers
  - AS exports only customer routes to a peer
  - AS exports a peer's routes only to its customers



Typical Export: Customer-Provider

- Customer pays provider for access to Internet
  - Provider exports its customer routes to everybody
  - Customer exports provider routes only to its customers