CS 5450

Inter-Domain Routing

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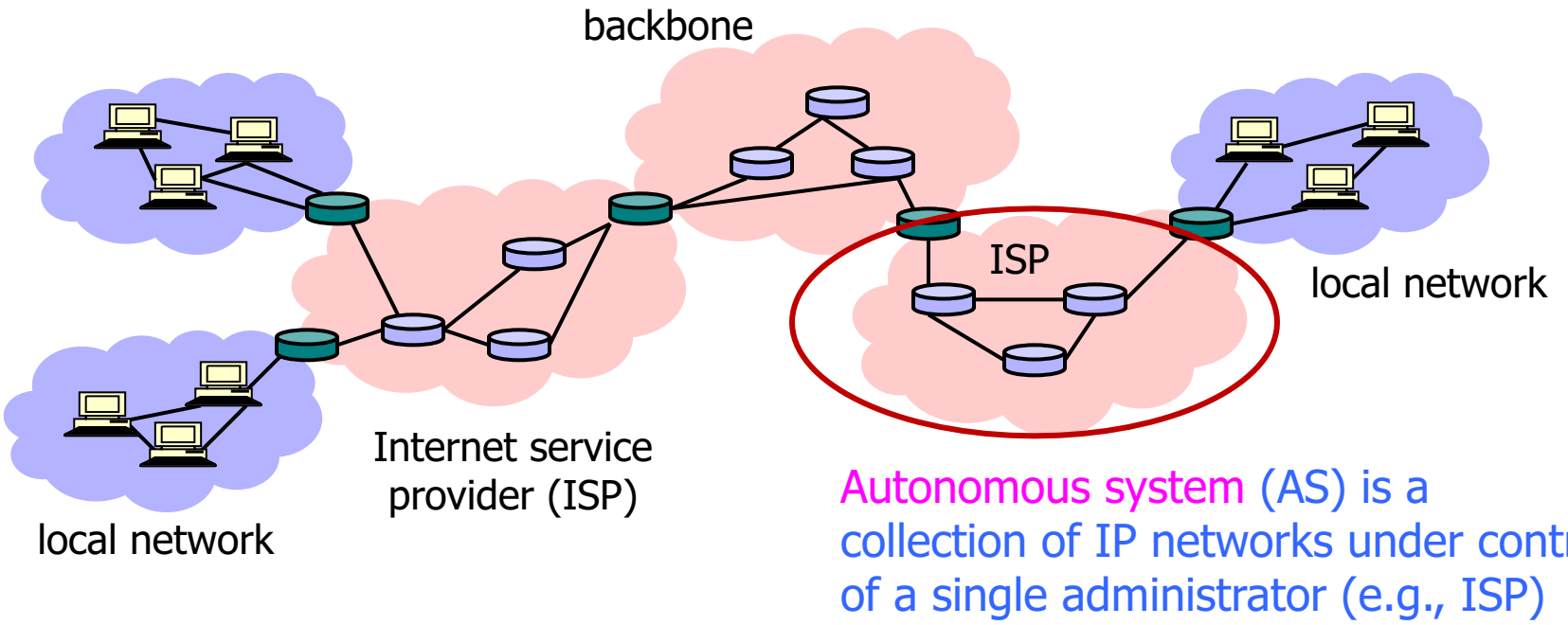
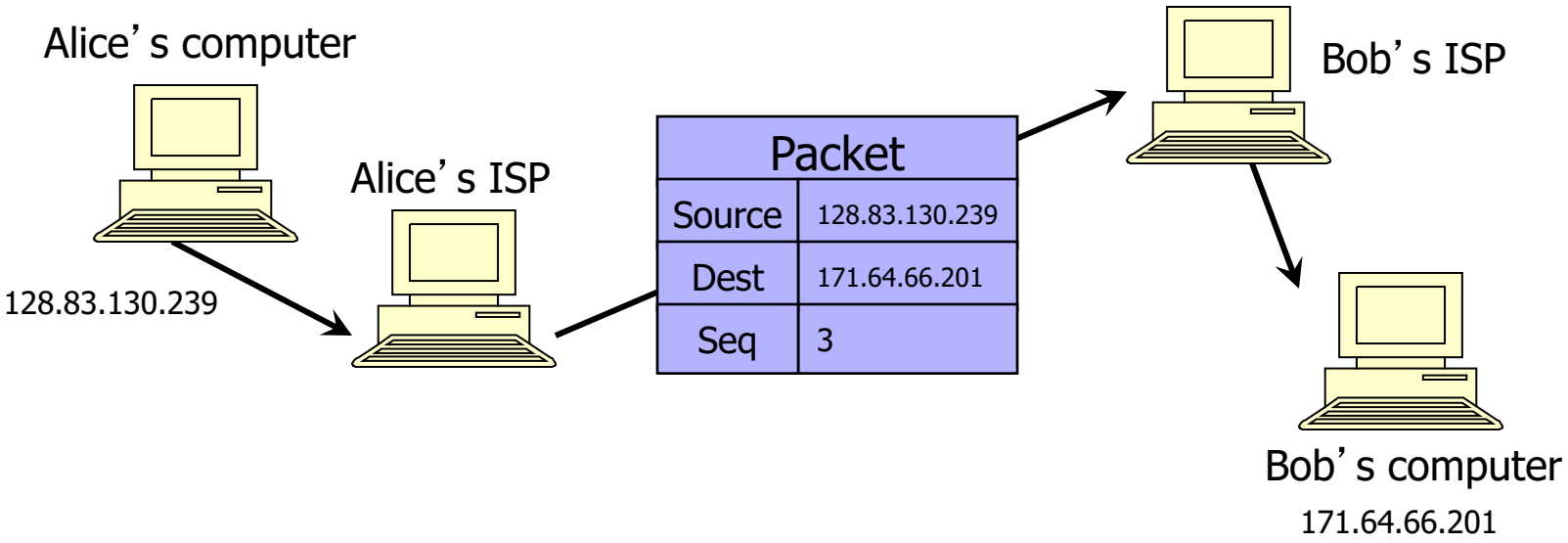
Internet Is a Network of Networks



- TCP/IP for packet routing and connections
- Border Gateway Protocol (BGP) for route discovery
- Domain Name System (DNS) for IP address discovery

IP (Internet Protocol)

- Connectionless
  - Unreliable, "best-effort" protocol
- Uses numeric addresses for routing
- Typically several hops in the route



IP Routing

- Routing of IP packets is based on IP addresses
  - 32-bit host identifiers (128-bit in IPv6)
- Routers use a forwarding table
  - Entry = destination, next hop, network interface, metric
  - Table look-up for each packet to decide how to route it
- Routers learn routes to hosts and networks via routing protocols
  - Host is identified by IP address, network by IP prefix
- BGP (Border Gateway Protocol) is the core Internet protocol for establishing inter-AS routes

Routing Table vs. Forwarding Table

- Forwarding table
  - Used when a packet is being forwarded
  - A row in the forwarding table contains the mapping from a network number to an outgoing interface and some MAC information, such as the Ethernet address of the next hop
- Routing table
  - Built by the routing algorithm as a precursor to build the forwarding table
  - Generally contains mapping from network numbers to next hops

Routing Table vs. Forwarding Table

(a)

Prefix/Length	Next Hop
18/8	171.69.245.10

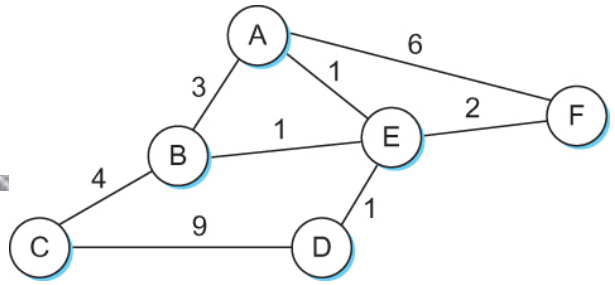
(b)

Prefix/Length	Interface	MAC Address
18/8	if0	8:0:2b:e4:b:1:2

Routing table

Forwarding table

Routing Problem

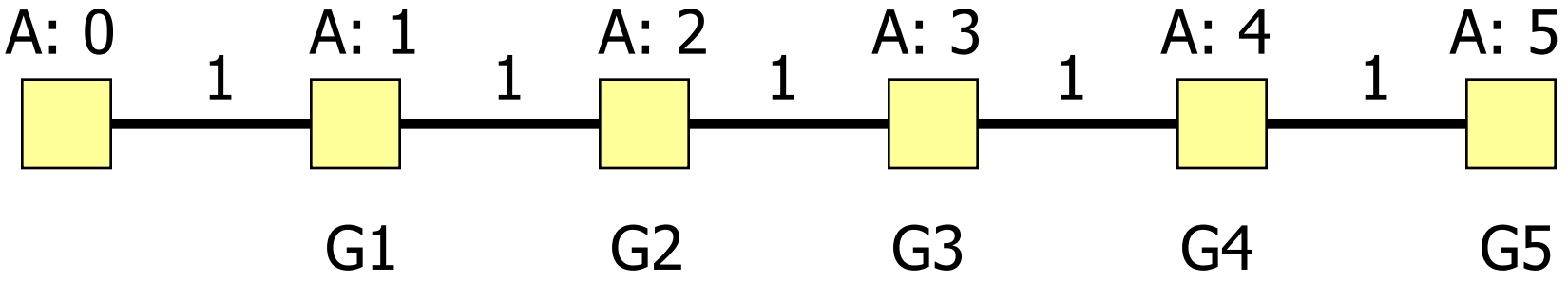


- Network as a graph
- Basic problem: find the lowest-cost path between any two nodes
  - Cost of a path = sum of the costs of all the edges that make up the path
- Topology is dynamic: need a distributed and dynamic protocol
- Two main classes of protocols
  - Distance Vector
  - Link State

Distance-Vector Routing

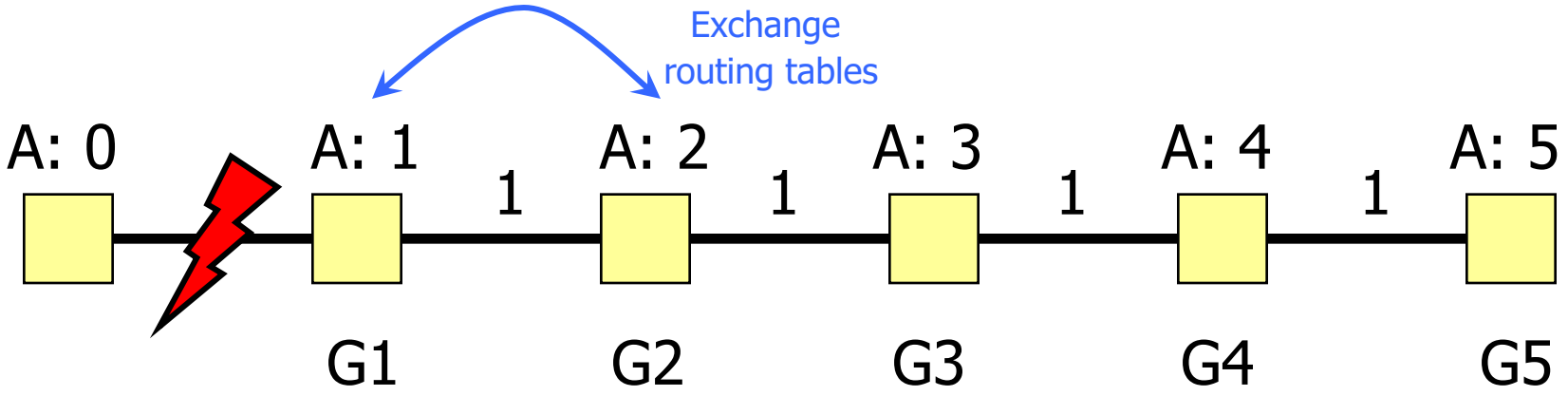
- Each node keeps vector with distances to all nodes
- Periodically sends distance vector to all neighbors
- Neighbors send their distance vectors, too; node updates its vector based on received information
  - Bellman-Ford algorithm: for each destination, router picks the neighbor advertising the cheapest route, adds his entry into its own routing table and re-advertises
  - Used in RIP (routing information protocol)
- Split-horizon update
  - Do not advertise a route on an interface from which you learned the route in the first place!

Good News Travels Fast



- G1 advertises route to network A with distance 1
- G2-G5 quickly learn the good news and install the routes to A via G1 in their local routing tables

Bad News Travels Slowly



- G1's link to A goes down
- G2 is advertising a pretty good route to G1 (cost=2)
- G1's packets to A are forever looping between G2 and G1
- G1 is now advertising a route to A with cost=3, so G2 updates its own route to A via G1 to have cost=4, and so on
  - G1 and G2 are slowly counting to infinity
  - Split-horizon updates only prevent two-node loops

Link-State Routing

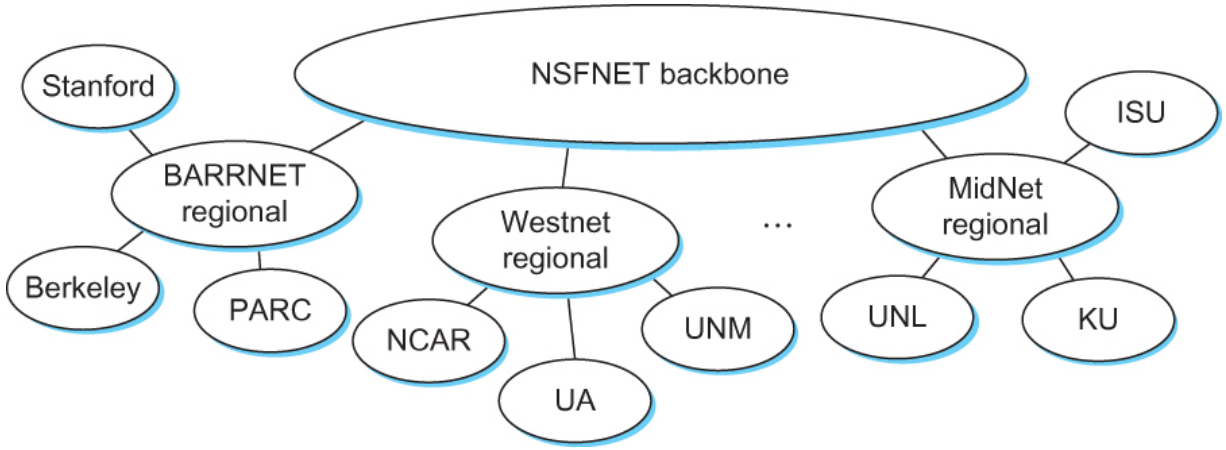
- Strategy: send to all nodes (not just neighbors) information about directly connected links (not entire routing table)
- Link-state packet (LSP)
  - ID of the node that created the LSP
  - Cost of link to each directly connected neighbor
  - Sequence number (SEQNO)
  - Time-to-live (TTL) for this packet

Reliable Flooding

- Store most recent LSP from each node
- Forward LSP to all nodes but one that sent it
- Generate new LSP periodically; increment SEQNO
- Start SEQNO at 0 when reboot
- Decrement TTL of each stored LSP, discard when TTL=0

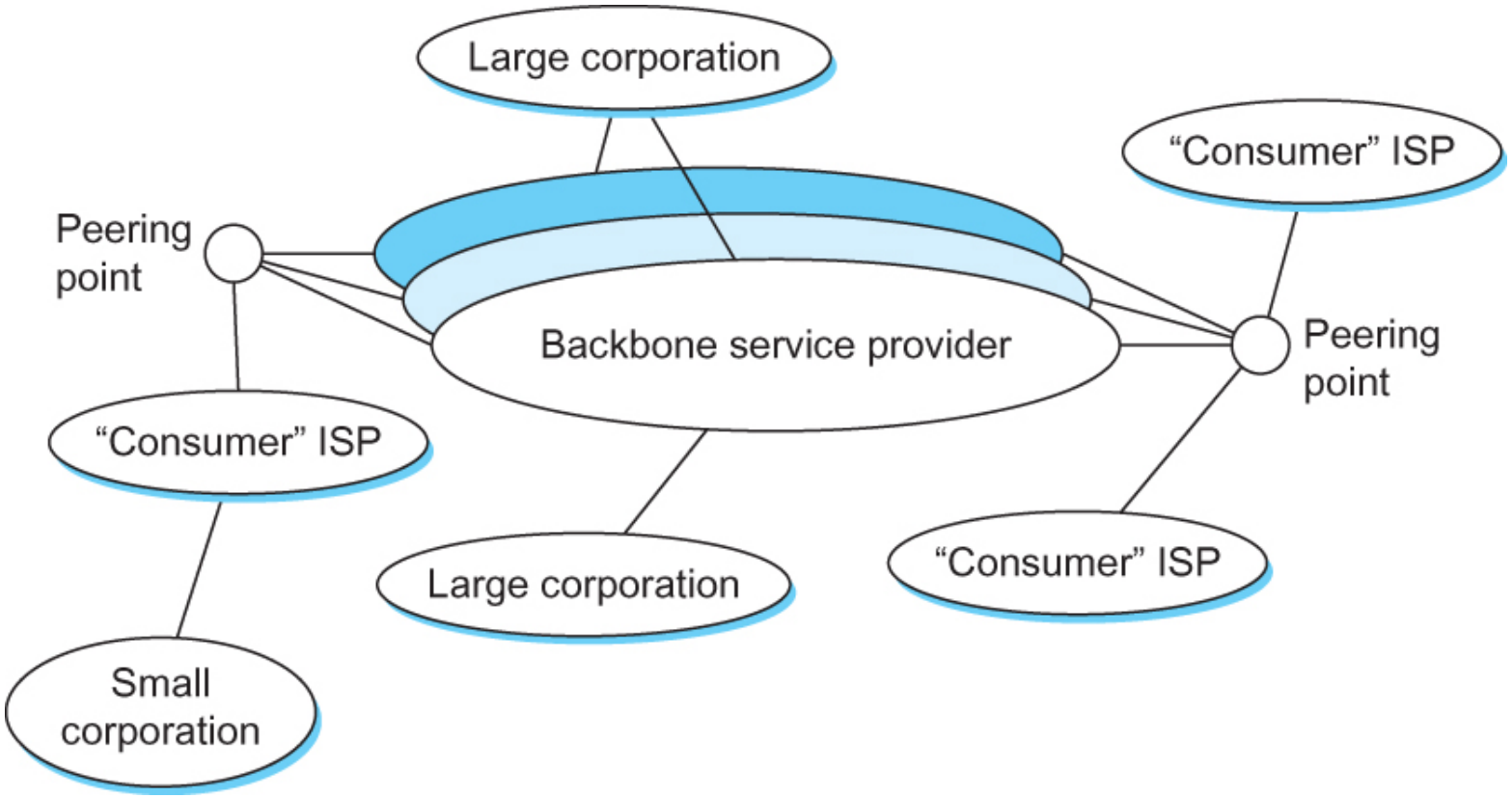
Inter-AS Routing

- Neither DV, nor LS scaled even to the Internet as it looked like in the 1990s



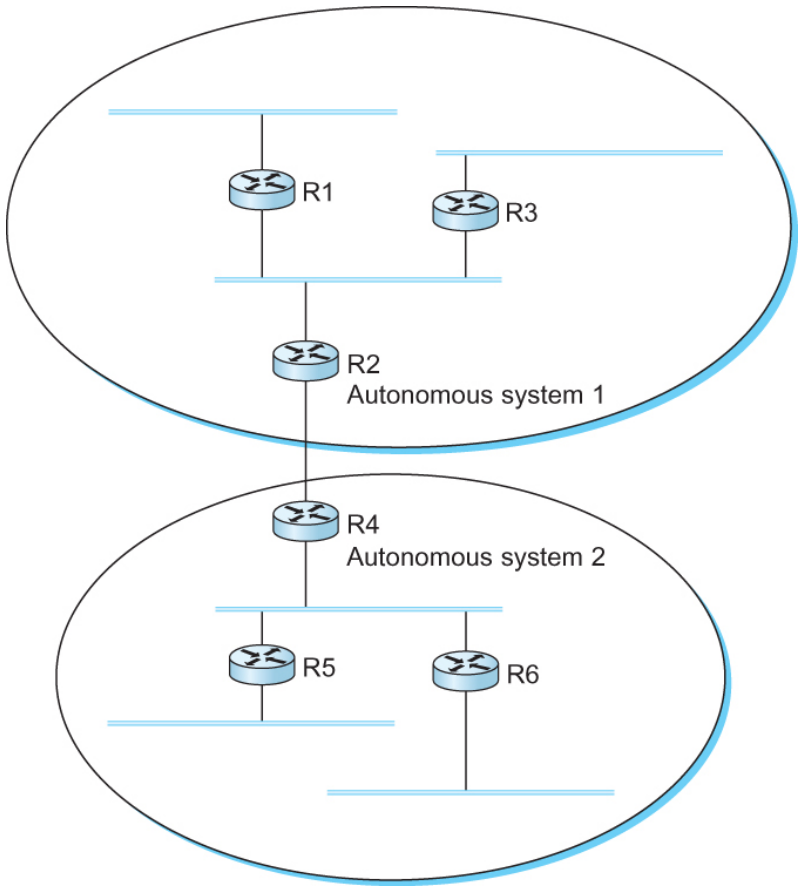
- Today need to handle hundreds of thousands of networks, billions of end nodes

Simple Model of Global Internet



Interdomain Routing

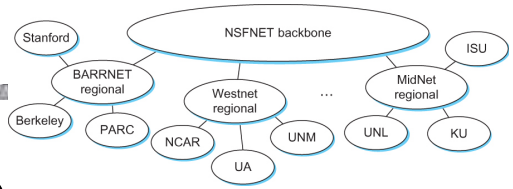
- Internet is organized as autonomous systems (AS), each of which is under the control of a single administrative entity
- Autonomous System (AS) corresponds to an administrative domain
  - Examples: university network, corporate internal network, backbone network, network of a single Internet service provider



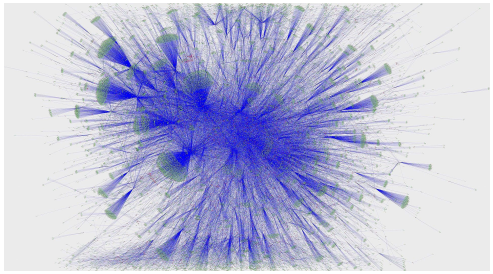
Route Propagation

- Idea: to improve scalability, hierarchically aggregate routing information in a large internet
- Divide the routing problem in two parts
  - Routing within a single autonomous system
  - Routing between autonomous systems
- Two-level route propagation hierarchy
  - Inter-domain routing protocol (Internet-wide standard)
  - Intra-domain routing protocol (each AS selects its own)

EGP and BGP



- Old Exterior Gateway Protocol (EGP)
  - Forced a tree-like topology onto the Internet
    - There is a single backbone and autonomous systems are connected only as parents and children and not as peers
  - Did not allow for the topology to become general
- Border Gateway Protocol (BGP)



  - Assumes that the Internet is an arbitrarily interconnected set of ASs
    - Today's Internet consists of an interconnection of multiple backbone networks (service provider networks operated by private companies rather than the government)
    - Sites are connected to each other in arbitrary ways

Inter-AS Connections

- Some large corporations connect directly to one or more of the backbones, while others connect to smaller, non-backbone service providers
- Many service providers exist mainly to provide service to "consumers" (individuals with computers and devices), and these providers must connect to the backbone providers
- Often many providers arrange to interconnect with each other at a single "peering point"

Types of Autonomous Systems

- Local traffic = traffic that originates at or terminates on nodes within an AS
- Transit traffic = traffic that passes through an AS
- Three types of ASs
  - Stub AS has only a single connection to one other AS; such an AS will only carry local traffic (small corp)
  - Multihomed AS has connections to more than one other AS, but refuses to carry transit traffic (large corp)
  - Transit AS has connections to more than one other AS, and is designed to carry both transit and local traffic (backbone provider)

Goals of BGP

- The goal of Inter-domain routing is to find any path to the intended destination that is loop-free
- Reachability rather than optimality!
  - Finding path anywhere close to optimal is considered to be a great achievement (why?)

BGP Challenges

- Scalability: a backbone router must be able to forward any packet to anywhere in the Internet
  - Routing table must have a match for any valid IP addr
- Full autonomy of the domains
  - Impossible to calculate meaningful cost for a path that crosses multiple ASs
  - A cost of 1000 might imply a great path from one provider and unacceptably bad from another provider
- Providers may not trust each other
  - One provider may not believe another's route advertisements

BGP Speakers

Each AS has...

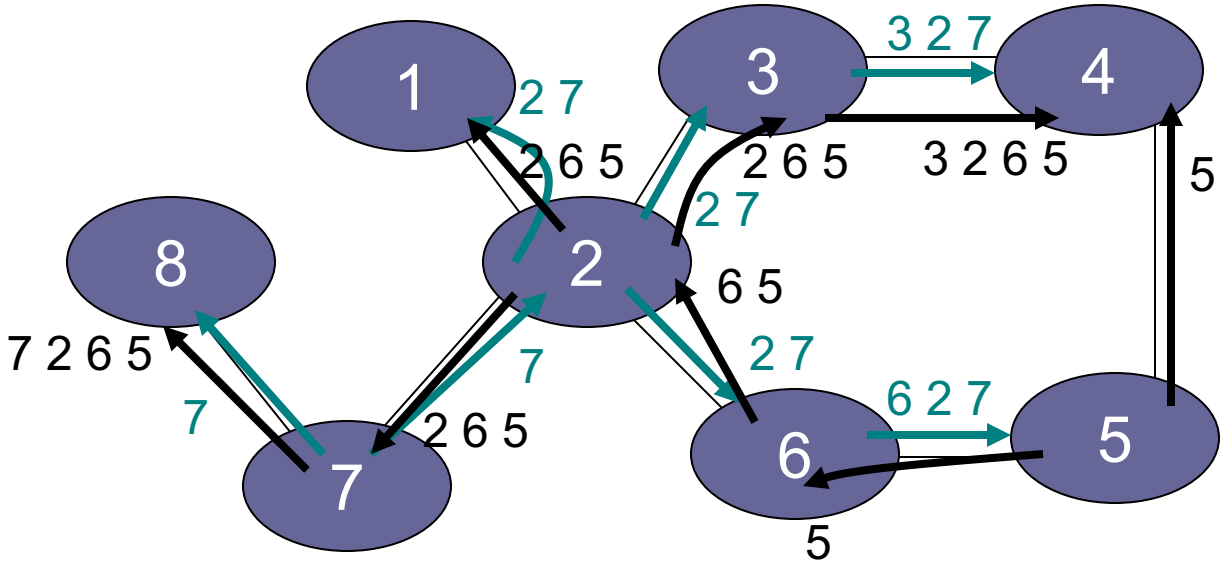
- One BGP speaker that advertises:
  - local networks
  - other reachable networks (transit AS only)
  - path information
- One or more border gateways (need not be the same as speakers)
  - Routers through which packets enter and leave the AS

Overview of BGP

- BGP is a path-vector protocol between ASes
- Just like distance-vector, but routing updates contain an actual path to destination node
  - The list of traversed ASes and the set of network prefixes belonging to the first AS on the list
- Each BGP router receives update messages from neighbors, selects one "best" path for each prefix, and advertises this path to its neighbors
  - Can be the shortest path, but doesn't have to be
    - "Hot-potato" vs. "cold-potato" routing
  - Always route to the most specific prefix for a destination

BGP Example

[Wetherall]

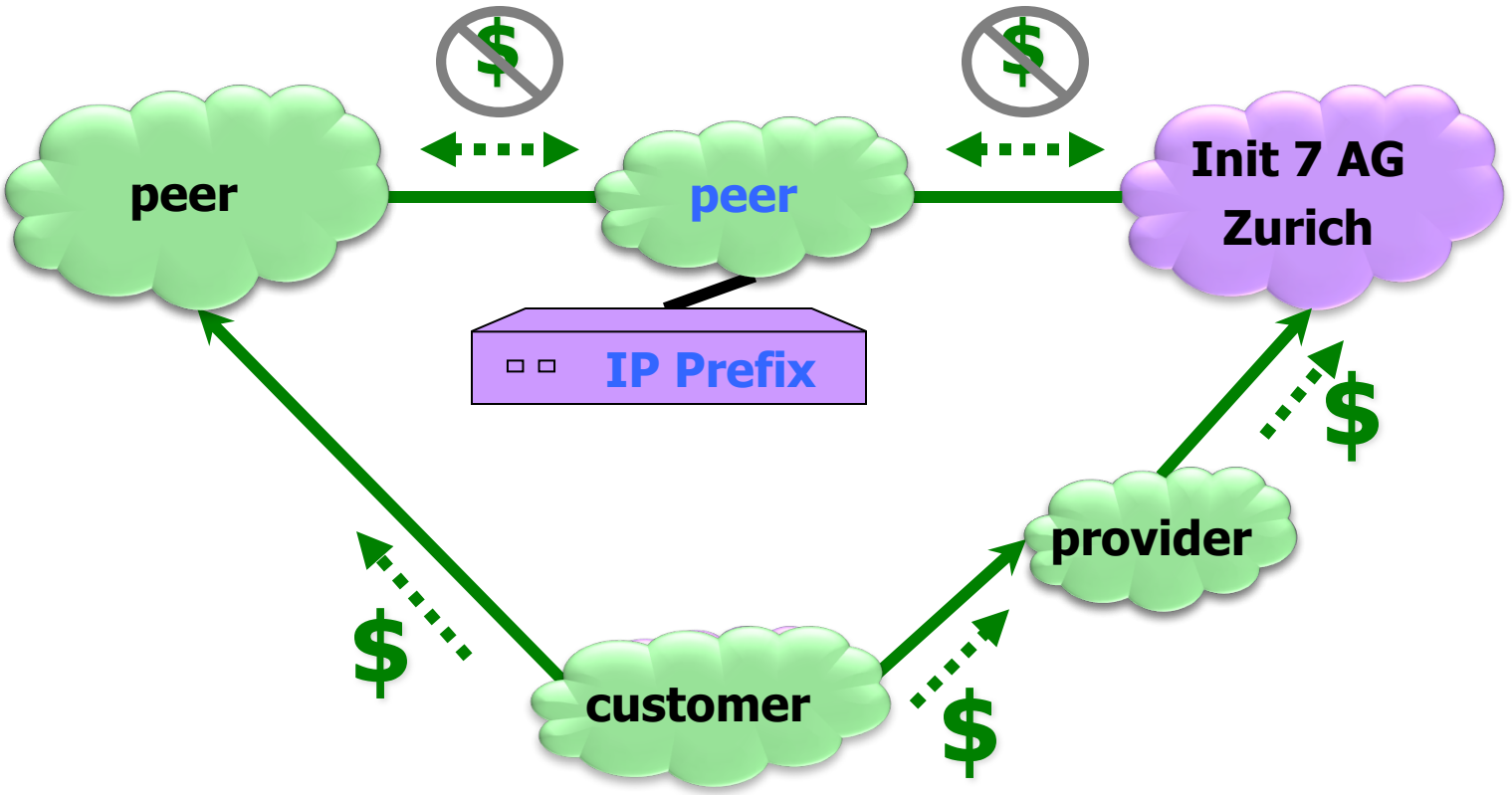


- AS 2 provides transit for AS 7
  - Traffic to and from AS 7 travels through AS 2

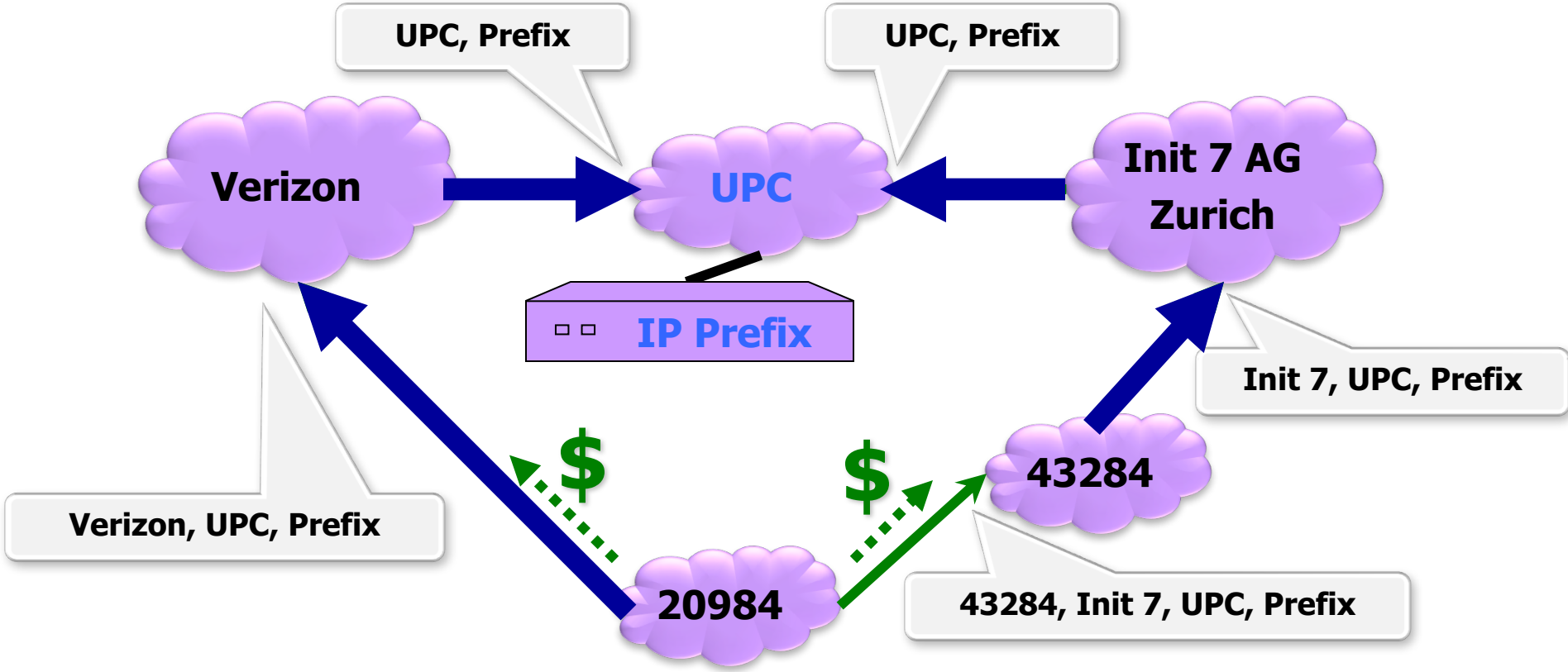
Some (Old) BGP Statistics

- BGP routing tables contain about 125,000 address prefixes mapping to about 17-18,000 paths
- Approx. 10,000 BGP routers
- Approx. 2,000 organizations own AS
- Approx. 6,000 organizations own prefixes
- Average route length is about 3.7
- 50% of routes have length less than 4 ASes
- 95% of routes have length less than 5 ASes

Illustration

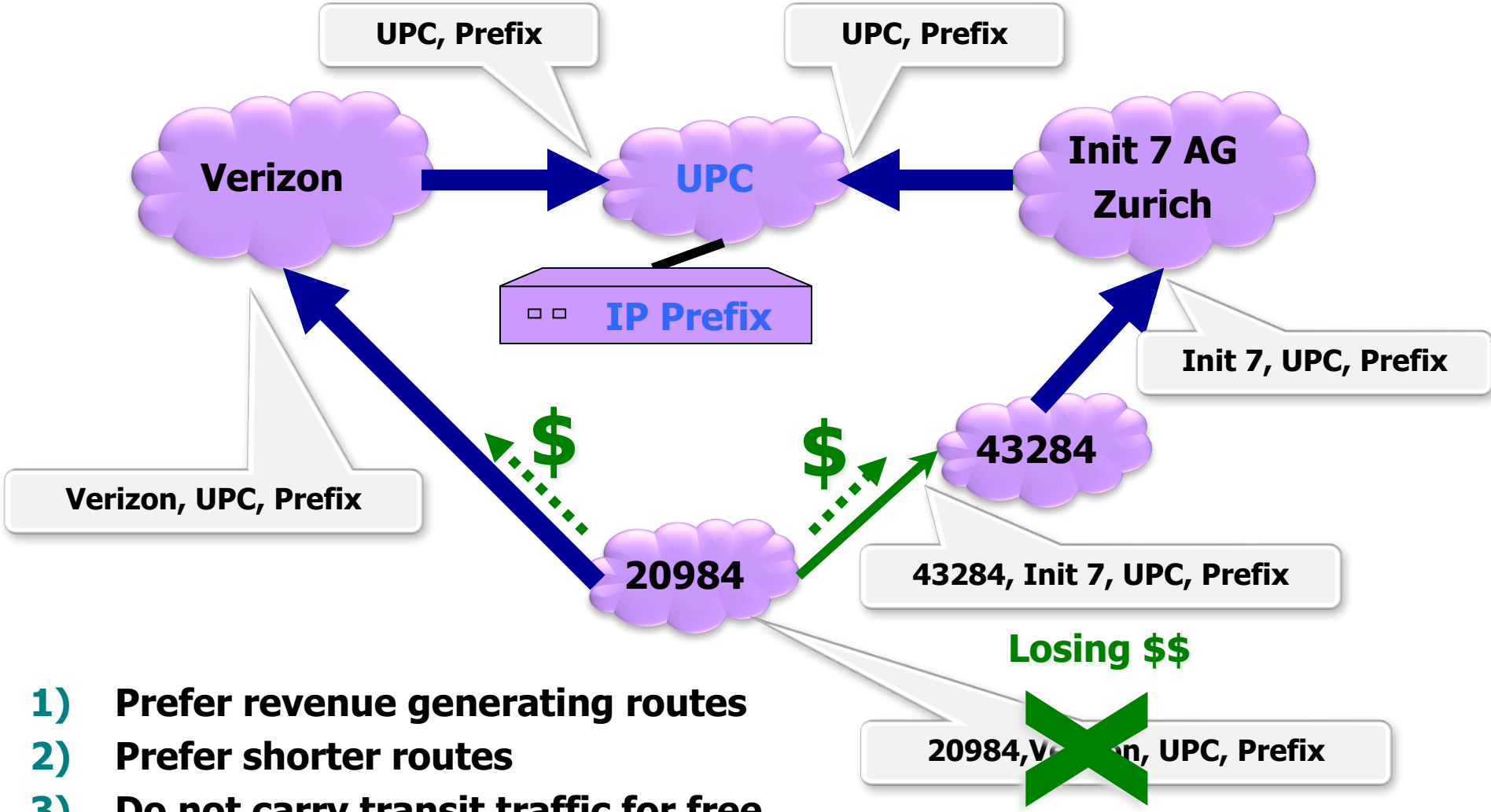


Routing with BGP



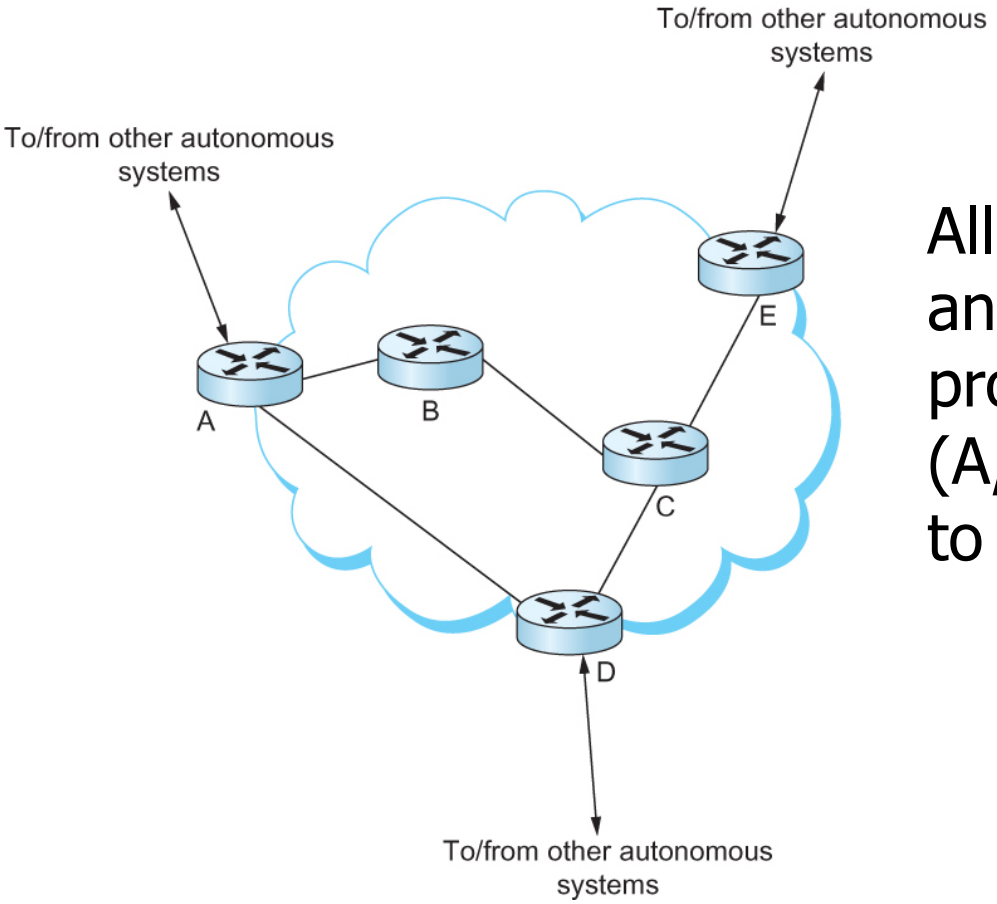
1) **Prefer revenue generating routes**
2) **Prefer shorter routes**

Routing with BGP



1) Prefer revenue generating routes
2) Prefer shorter routes
3) Do not carry transit traffic for free

Integrating Inter- and Intra-Domain

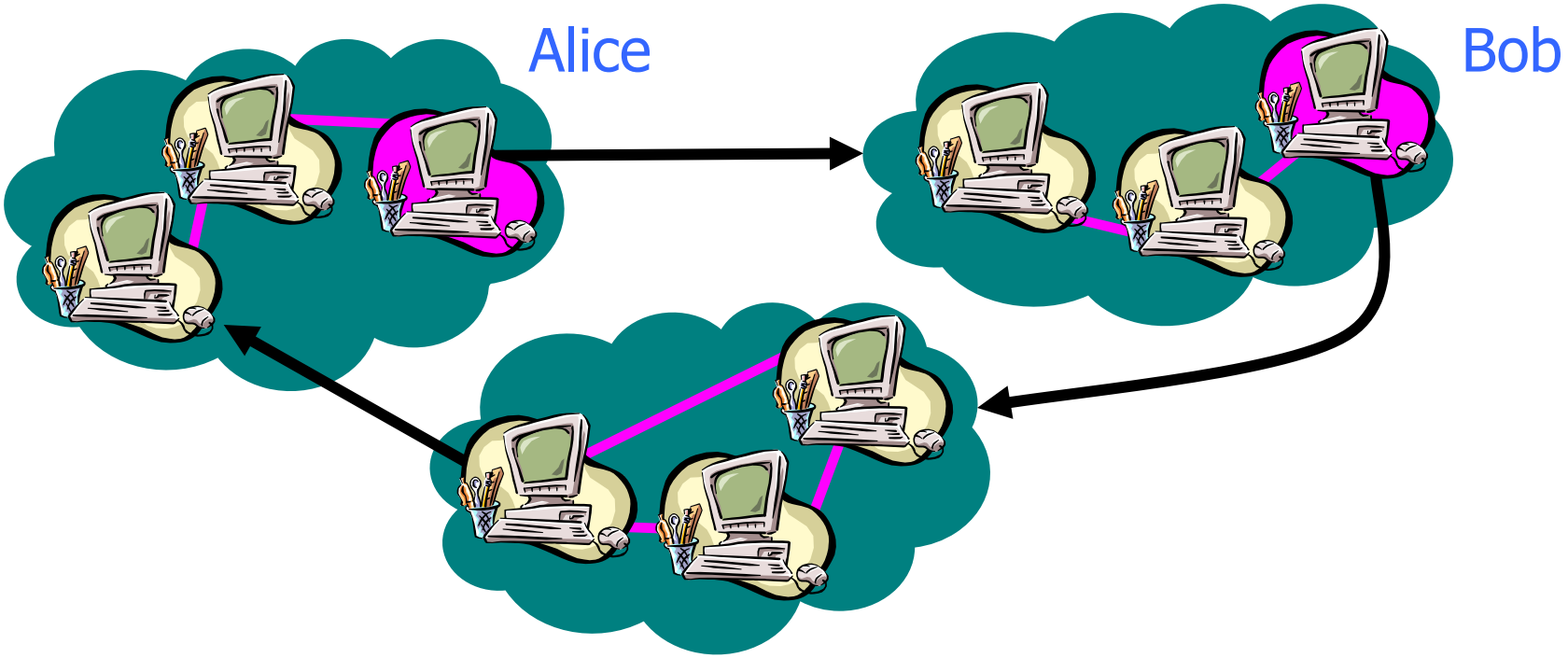


All routers run iBGP and an intradomain routing protocol. Border routers (A, D, E) also run eBGP to other ASs.

BGP Issues

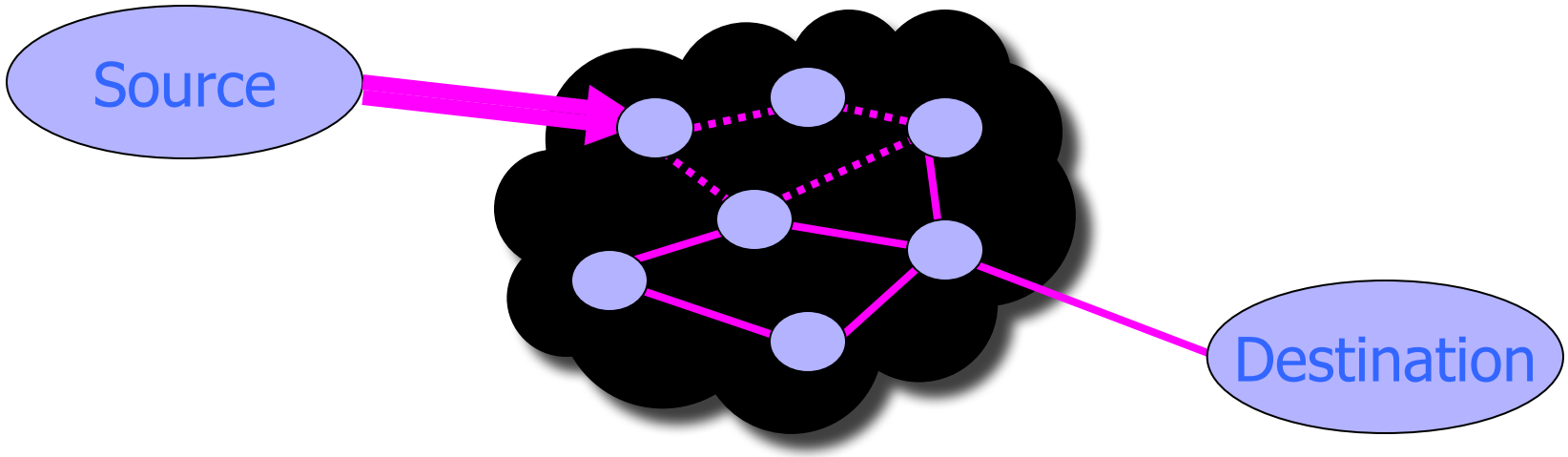
- BGP convergence problems
  - Protocol allows policy flexibility
  - Some legal policies prevent convergence
  - Even shortest-path policy converges slowly
- Incentive for dishonesty
  - ISP pays for some routes, others free
- Security problems
  - Potential for disruptive attacks

Evidence: Asymmetric Routes



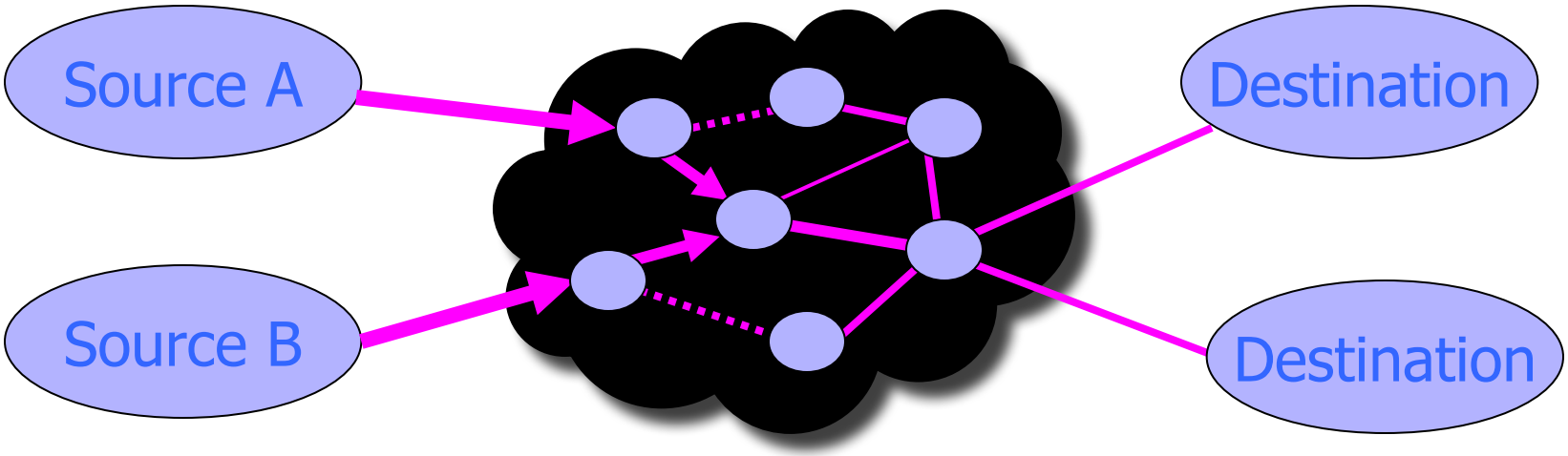
- Alice, Bob use cheapest routes to each other
  - Cheapest is not always shortest!
- Asymmetic routes are prevalent
  - AS asymmetry in 30% of measured routes
  - Finer-grained asymmetry far more prevalent

Side Note: TCP Congestion Control



- If packets are lost, assume congestion
  - Reduce transmission rate by half, repeat
  - If loss stops, increase rate very slowly
  - Design assumes routers blindly obey this policy

Protocol Rewards Dishonesty



- Amiable Alice yields to boisterous Bob
  - Alice and Bob both experience packet loss
  - Alice backs off
  - Bob disobeys protocol, gets better results

BGP Misconfiguration

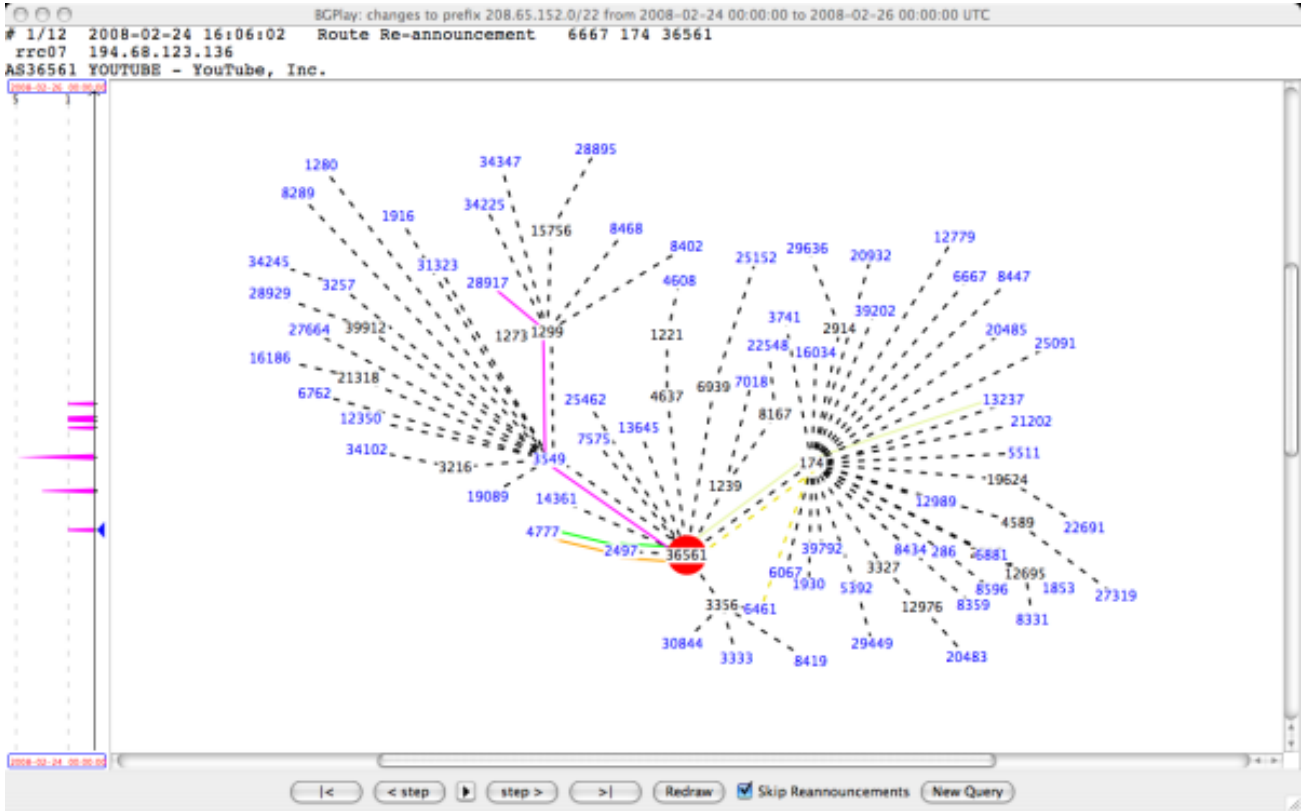
- Domain advertises good routes to addresses it does not know how to reach
  - Result: packets go into a network "black hole"
- April 25, 1997: "The day the Internet died"
  - AS7007 (Florida Internet Exchange) de-aggregated the BGP route table and re-advertised all prefixes as if it originated paths to them
    - In effect, AS7007 was advertising that it has the best route to every host on the Internet
  - Huge network instability as incorrect routing data propagated and routers crashed under traffic

BGP (In)Security

- BGP update messages contain no authentication or integrity protection
- Attacker may falsify the advertised routes
  - Modify the IP prefixes associated with a route
    - Can blackhole traffic to certain IP prefixes
  - Change the AS path
    - Either attract traffic to attacker's AS, or divert traffic away
    - Interesting economic incentive: an ISP wants to dump its traffic on other ISPs without routing their traffic in exchange
  - Re-advertise/propagate AS path without permission
    - For example, a multi-homed customer may end up advertising transit capability between two large ISPs

YouTube (Normally)

- AS36561 (YouTube) advertises 208.65.152.0/22



February 24, 2008

- Pakistan government wants to block YouTube

Corrigendum- Most Urgent

GOVERNMENT OF PAKISTAN
PAKISTAN TELECOMMUNICATION AUTHORITY
ZONAL OFFICE PESHAWAR
Plot-11, Sector A-3, Phase-V, Hayatabad, Peshawar.
Ph: 091-9217279- 5829177 Fax: 091-9217254
www.pta.gov.pk

NWFP-33-16 (BW)/06/PTA February ,2008

Subject: **Blocking of Offensive Website**

Reference: This office letter of even number dated 22.02.2008.

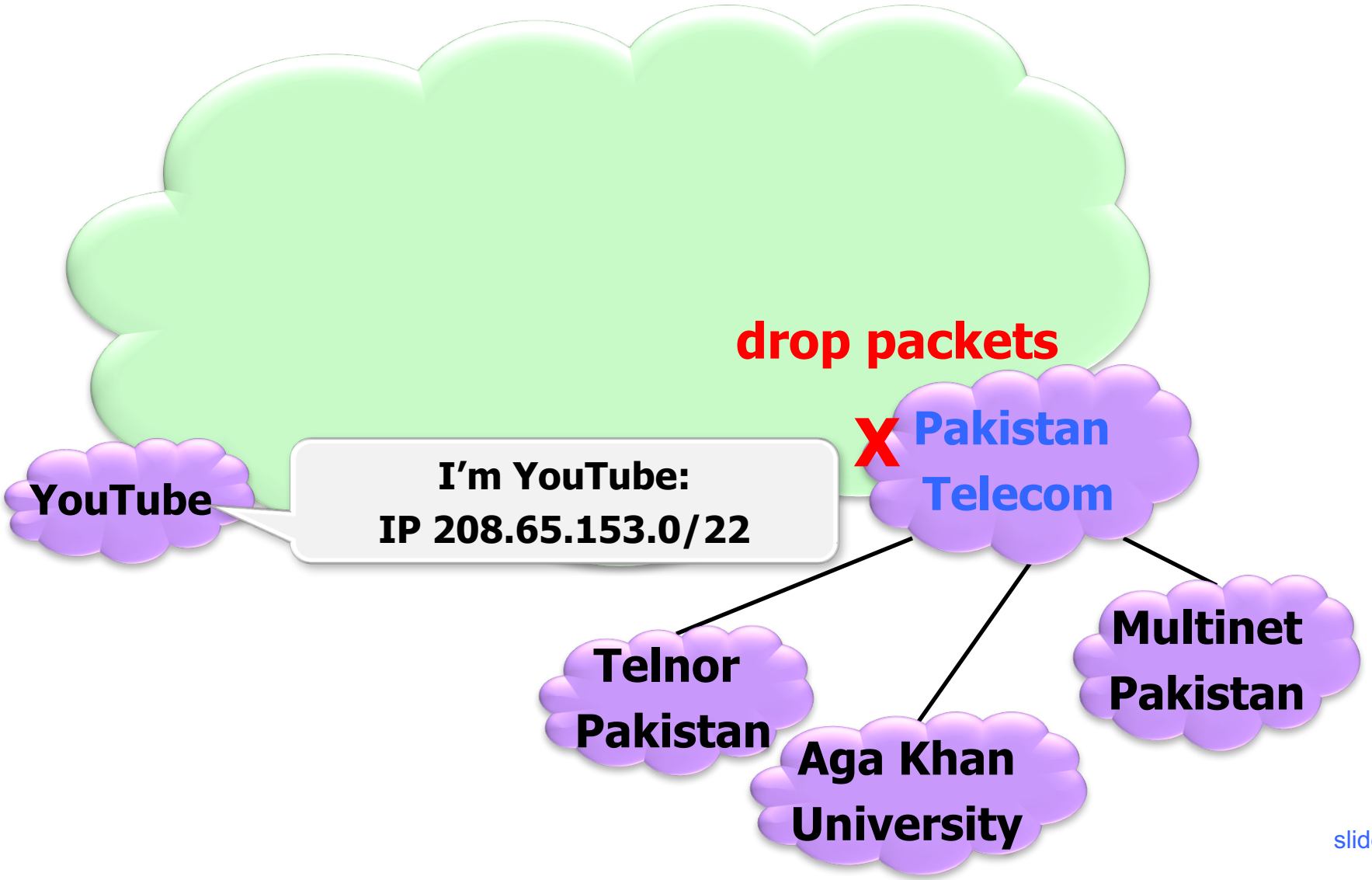
I am directed to request all ISPs to immediately block access to the following website

URL: http://www.youtube.com/watch?v=o3s8jtvvg00

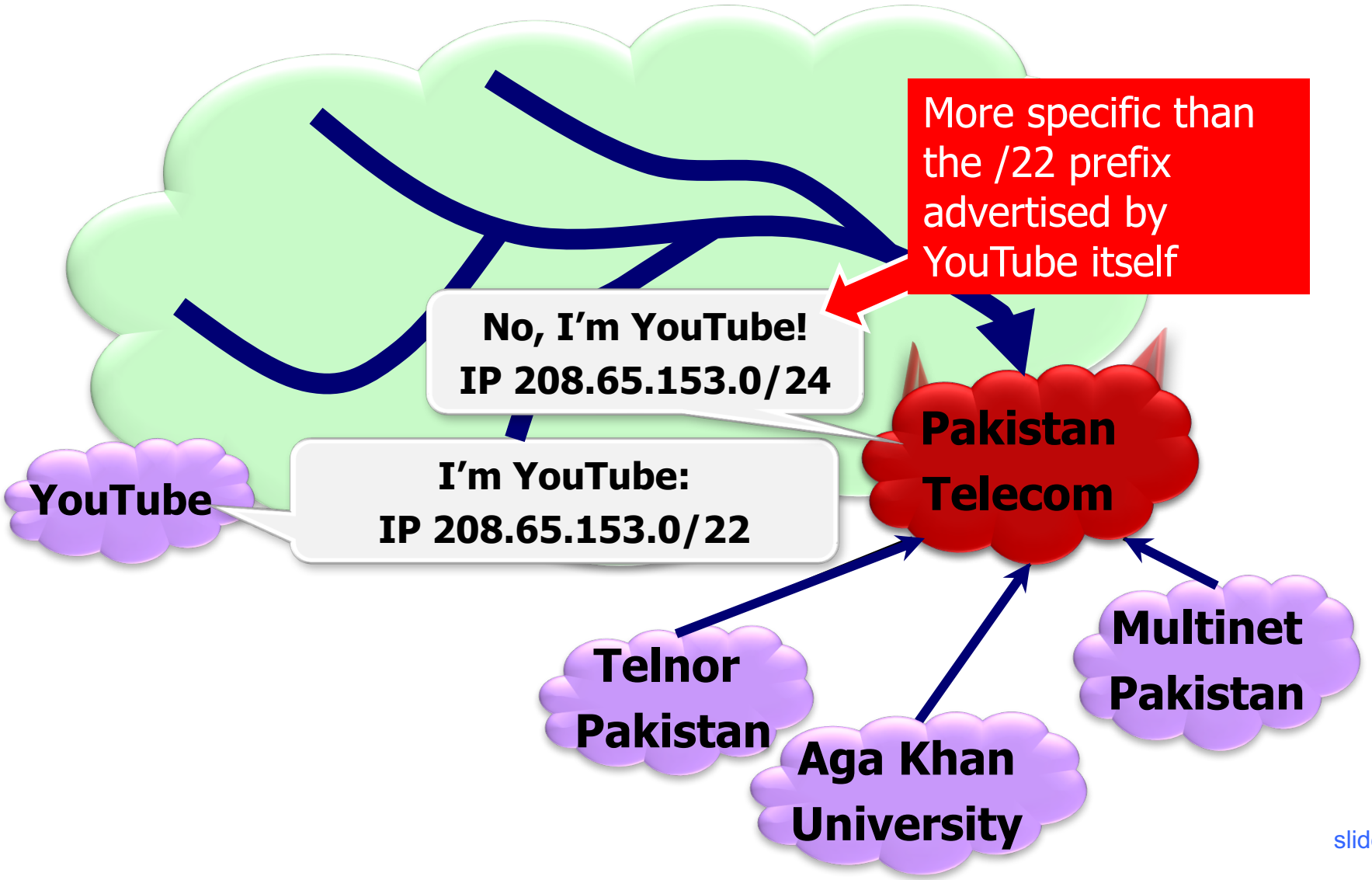
IPs: 208.65.153.238, 208.65.153.253, 208.65.153.251

Compliance report should reach this office through return fax or at email peshawar@pta.gov.pk today please.

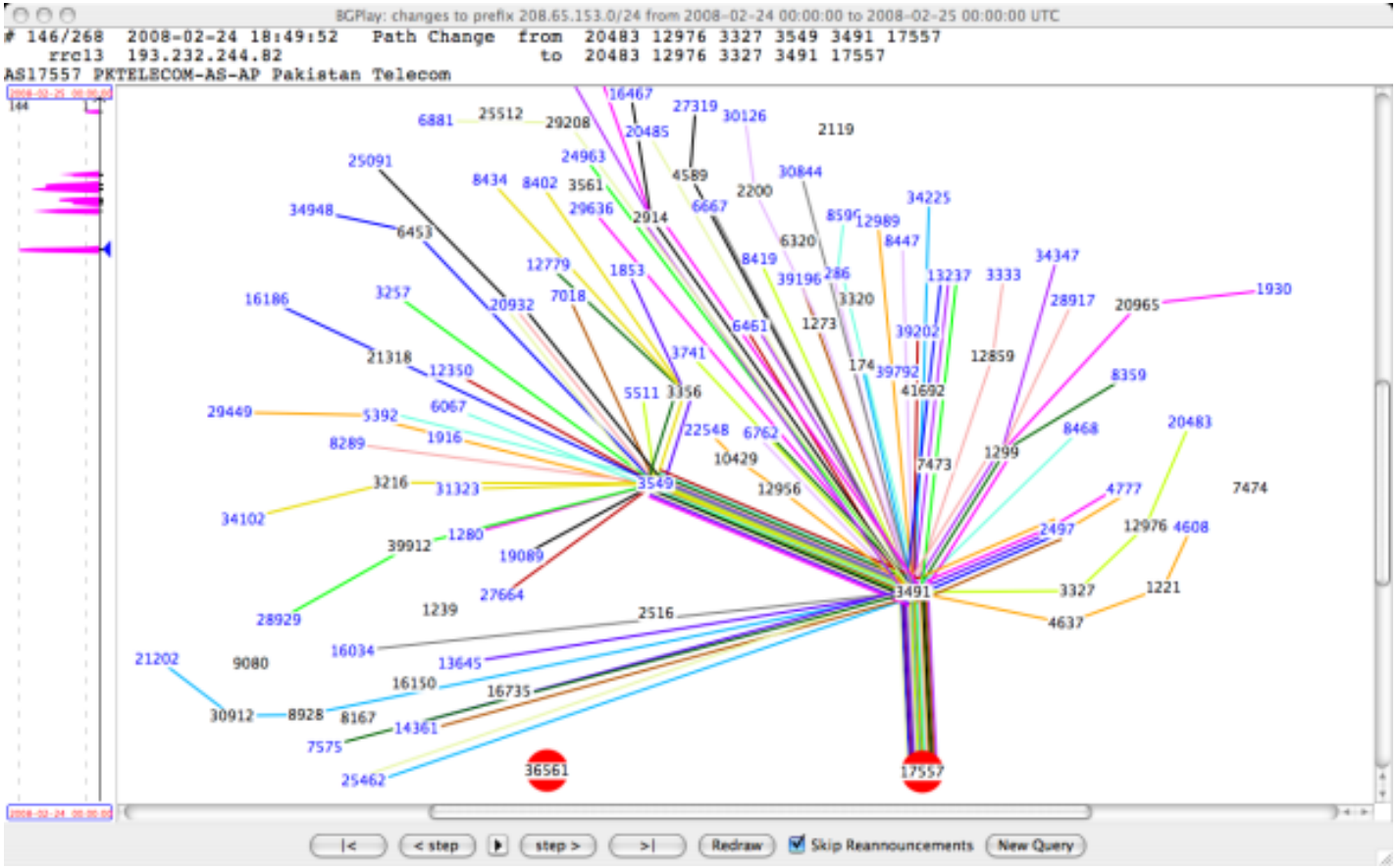
What Should've Happened



What Did Happen



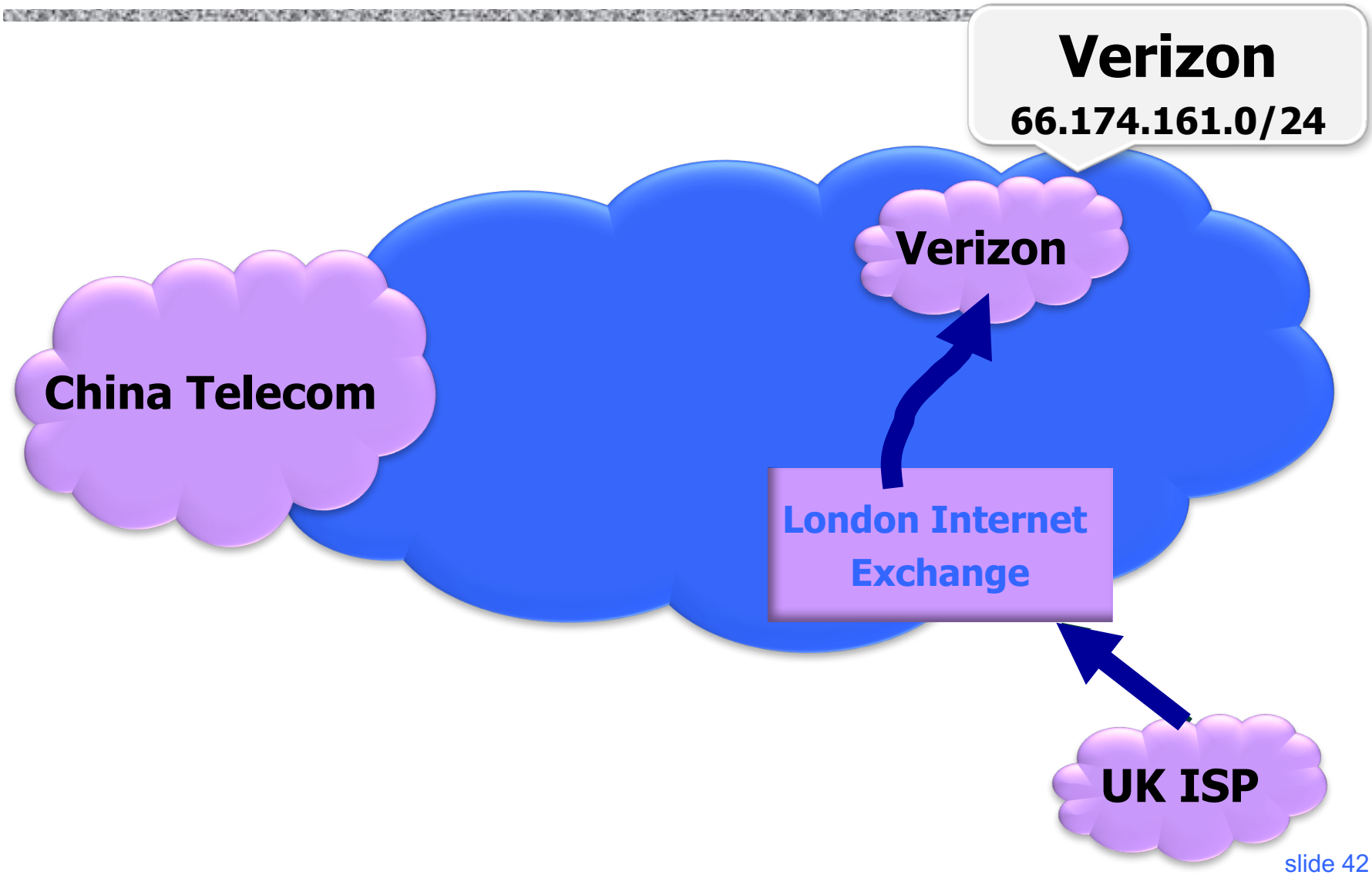
Two-Hour YouTube Outage



Other BGP Incidents

- May 2003: Spammers hijack unused block of IP addresses belonging to Northrop Grumman
  - Entire Northrop Grumman ends up on spam blacklist
  - Took two months to reclaim ownership of IP addresses
- Dec 2004: Turkish ISP advertises routes to the entire Internet, including Amazon, CNN, Yahoo
- Apr 2010: Small Chinese ISP advertises routes to 37,000 networks, incl. Dell, CNN, Apple
- Feb-May 2014: Someone uses BGP to hijack the addresses of Bitcoin mining-pool servers, steals $83,000 worth of Bitcoins

China Telecom Incident



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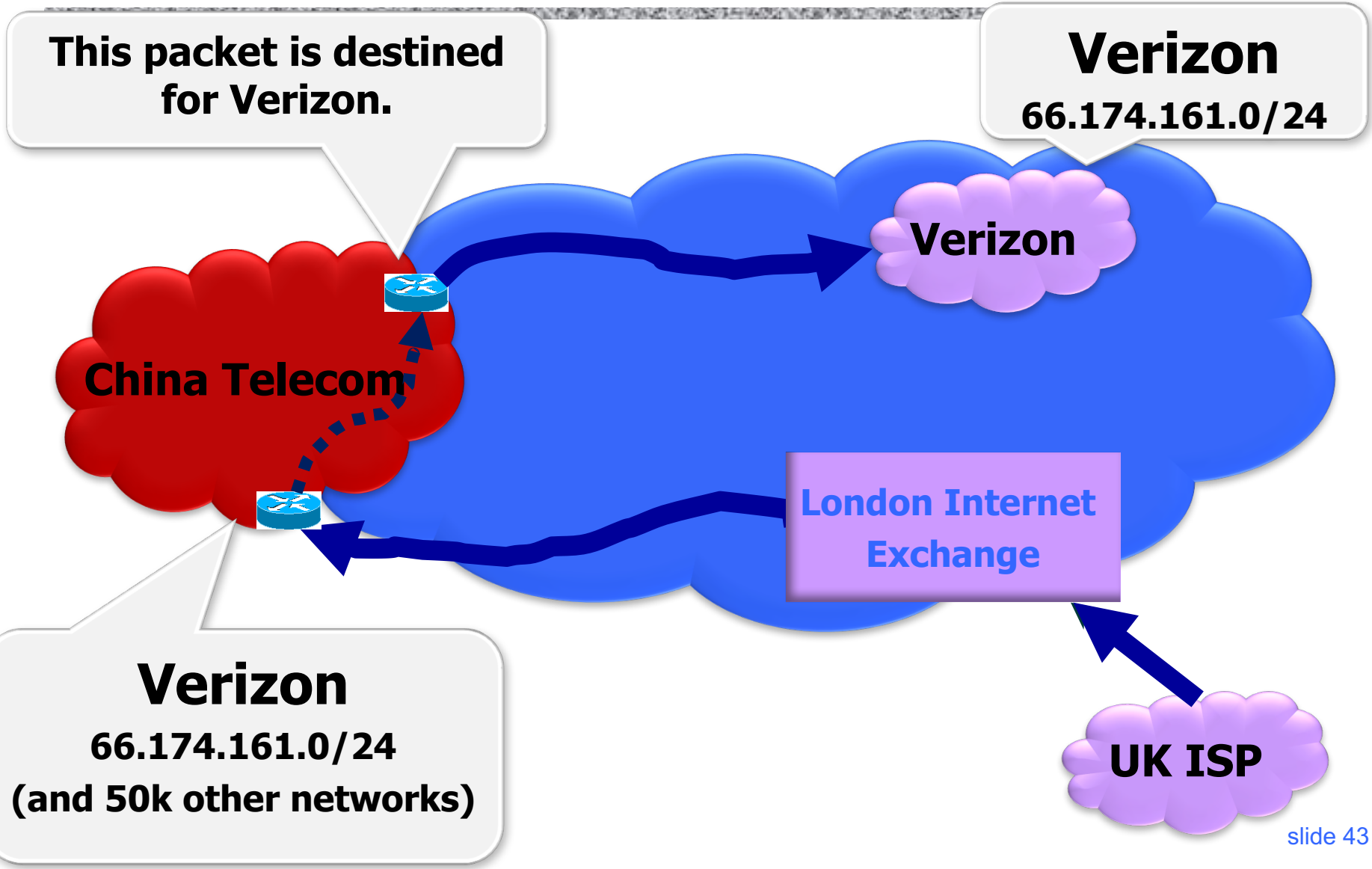


IP Address Ownership & Hijacking

- IP address block assignment
  - Regional Internet Registries (ARIN, RIPE, APNIC)
  - Internet Service Providers
- Proper origination of a prefix into BGP
  - By the AS who owns the prefix
  - … or, by its upstream provider(s) in its behalf
- However, what's to stop someone else?
  - Prefix hijacking: another AS originates the prefix
  - BGP does not verify that the AS is authorized
  - Registries of prefix ownership are inaccurate

Hijacking is Hard to Debug

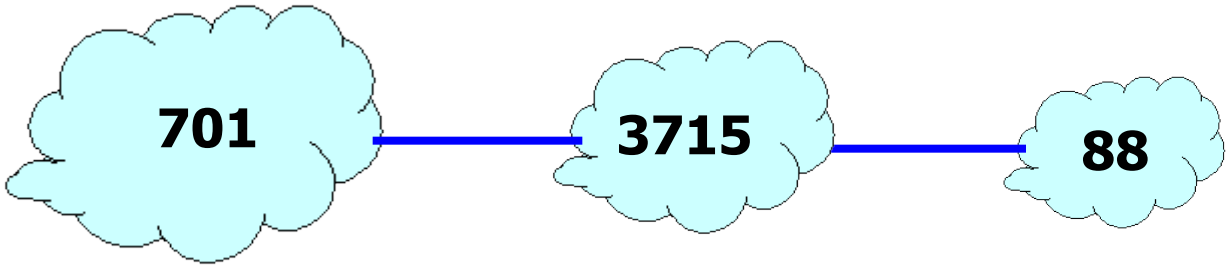
- The victim AS doesn't see the problem
  - Picks its own route
  - Might not even learn the bogus route
- May not cause loss of connectivity
  - E.g., if the bogus AS snoops and redirects
  - … may only cause performance degradation
- Or, loss of connectivity is isolated
  - E.g., only for sources in parts of the Internet
- Diagnosing prefix hijacking
  - Analyzing updates from many vantage points
  - Launching traceroute from many vantage points

Preventing Prefix Hijacking

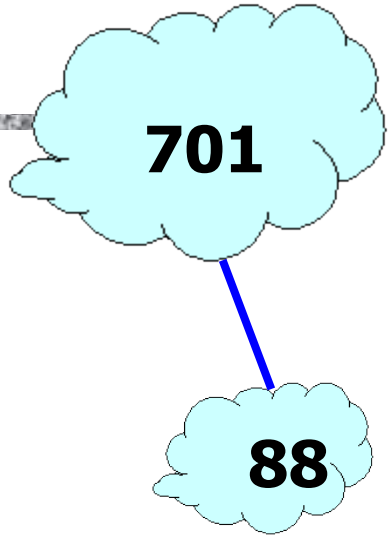
- Origin authentication
  - Secure database lists which AS owns which IP prefix
- soBGP
  - Digitally signed certificates of prefix ownership
- Prefix hijacking is not the only threat… in general, BGP allows ASes to advertise bogus routes
  - Remove another AS from a path to make it look shorter, more attractive, get paid for routing traffic
  - Add another AS to a path to trigger loop detection, make your connectivity look better

Bogus AS Paths

- Remove ASes from the AS path
  - E.g., turn "701 3715 88" into "701 88"
- Possible motivations
  - Make the AS path look shorter than it is
  - Attract sources that normally try to avoid AS 3715



Bogus AS Paths



- Add ASes to the path
  - E.g., turn "701 88" into "701 3715 88"
- Possible motivations
  - Trigger loop detection in AS 3715
  - Make your AS look like is has richer connectivity

Protecting BGP

- Simple authentication of packet sources and packet integrity is not enough
- Before AS advertises a set of IP addresses, the owner of these addresses must authorize it
  - Goal: verify path origin
- Each AS along the path must be authorized by the preceding AS to advertise the prefixes contained in the UPDATE message
  - Goal: verify propagation of the path vector

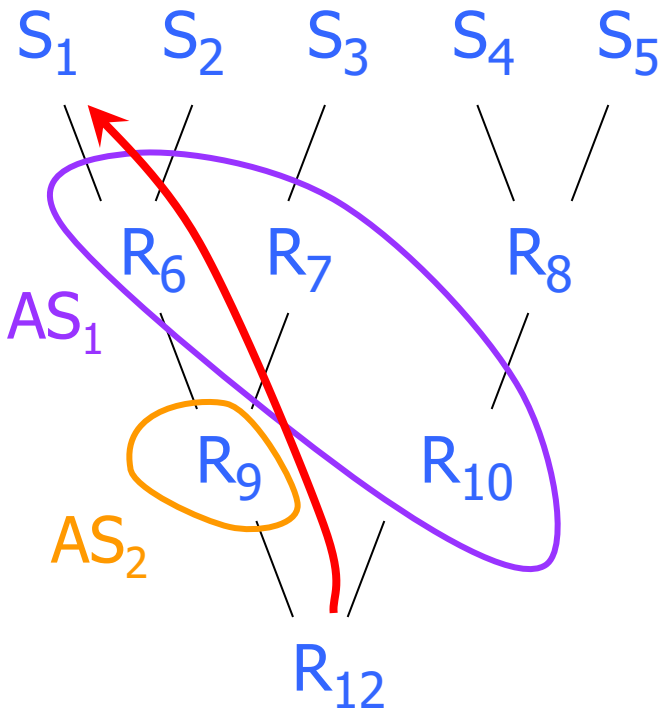
S-BGP Protocol

[Kent, Lynn, Seo]

- Address attestation
  - Owner of one or more prefixes certifies that the origin AS is authorized to advertise the prefixes
  - Need a public-key infrastructure (PKI)
    - X.509 certificates prove prefix ownership; owner can then delegate his “prefix advertising rights” to his ISP
- Route attestation
  - Router belonging to an AS certifies (using digital signatures) that the next AS is authorized to propagate this route advertisement to its neighbors
  - Need a separate public-key infrastructure
    - Certificates prove that AS owns a particular router

S-BGP Update Message

- An update message from R_9 advertising this route must contain:
  - Ownership certificate certifying that some X owns IP address S_1
  - Signed statement from X that AS_1 is authorized to advertise S_1
  - Ownership certificate certifying that AS_1 owns router R_6
    - If AS is represented by a router
  - Signed statement from R_6 that AS_2 is authorized to propagate AS_1's routes
  - Ownership certificate certifying that AS_2 owns router R_9
  - Lots of public-key operations!



Securing BGP

- Dozens of proposals, various combinations of cryptographic mechanisms and anomaly detection
  - Example: Secure BGP (S-BGP)
    - Origin authentication + entire AS path digitally signed
    - Can verify that the route is recent, no ASes have been added or removed, the order of ASes is correct
  - Also: IRV, SPV, psBGP, PGBGP, PHAS, Whisper…
- How many of these have been deployed?

None

- No complete, accurate registry of prefix ownership
- Need a public-key infrastructure
- Cannot react rapidly to changes in connectivity
- Cost of cryptographic operations
- Not deployable incrementally