COS 461: Computer Networks
Course Review
(12 weeks in 80 minutes)

Spring 2009 (MW 1:30-2:50 in CS 105)

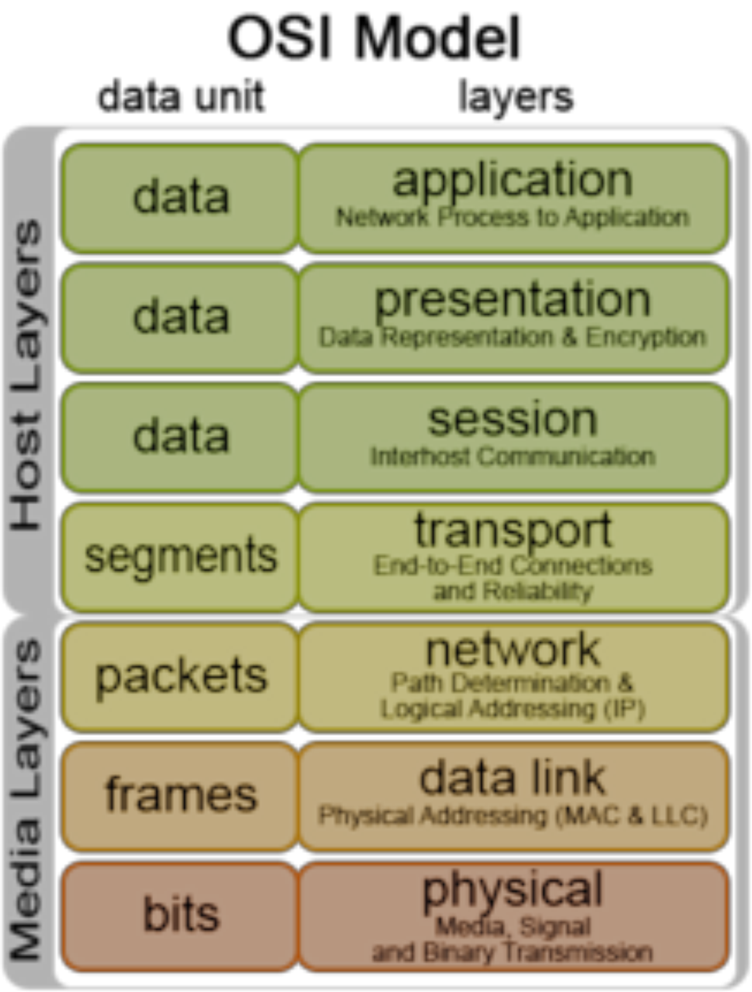
Mike Freedman

Teaching Assistants: Wyatt Lloyd and Jeff Terrace

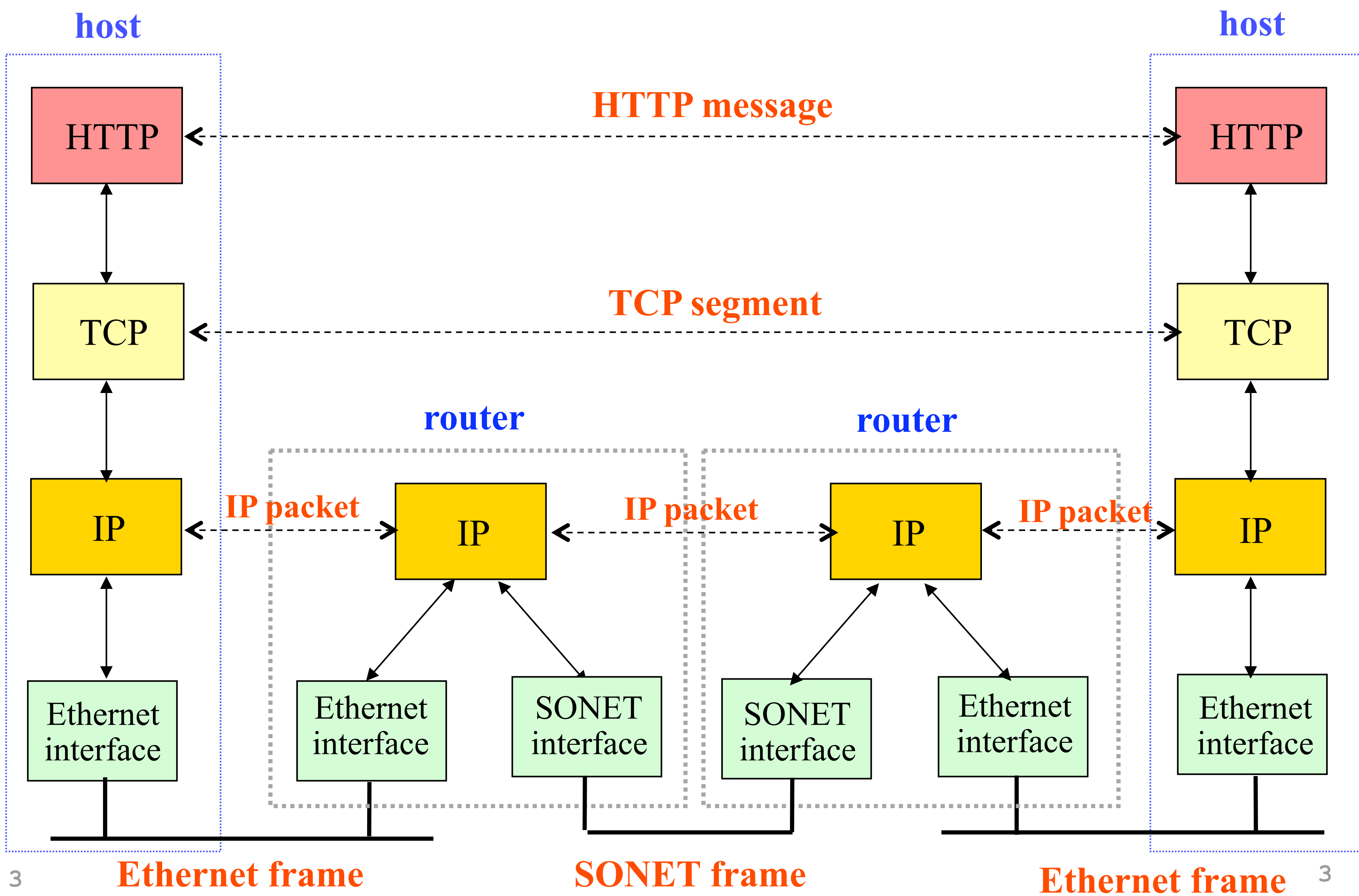
http://www.cs.princeton.edu/courses/archive/spr09/cos461/

What You (hopefully) Learned in This Course

- Skill: network programming
  - Socket programming
  - Implementing protocols
- Knowledge: how Internet works
  - IP protocol suite
  - Internet architecture
  - Applications (Web, DNS, P2P, …)
- Insight: key concepts
  - Protocols
  - Resource allocation
  - Naming
  - Layering



Message, Segment, Packet, and Frame



Topics

- Link layer:
  - Ethernet and CSMA/CD
  - Wireless protocols and CSMA/CA
  - Spanning tree, switching and bridging
  - Translating addrs: DHCP and ARP
- Network layer:
  - IPv4, addressing, and forwarding
  - IP routing
    - Link-state and distance vector
    - BGP: path vector, policies
  - IP multicast and anycast
  - Middleboxes: NATs, firewalls
  - Tunneling: MPLS, IPSec
  - Addt. Considerations: mobility, DTNs
- Transport layer:
  - Socket interface
  - UDP
  - TCP
    - Reliability
    - Congestion Control
  - Reliable multicast
- Application layer:
  - Translating names: DNS
  - HTTP and CDNs
  - Overlay networks
  - Peer-to-peer and DHTs
  - Email

Link Layer

Link-Layer Services

- Encoding
  - Representing the 0s and 1s
- Framing
  - Encapsulating packet into frame, adding header and trailer
  - Using MAC addresses, rather than IP addresses
- Error detection
  - Errors caused by signal attenuation, noise.
  - Receiver detecting presence of errors

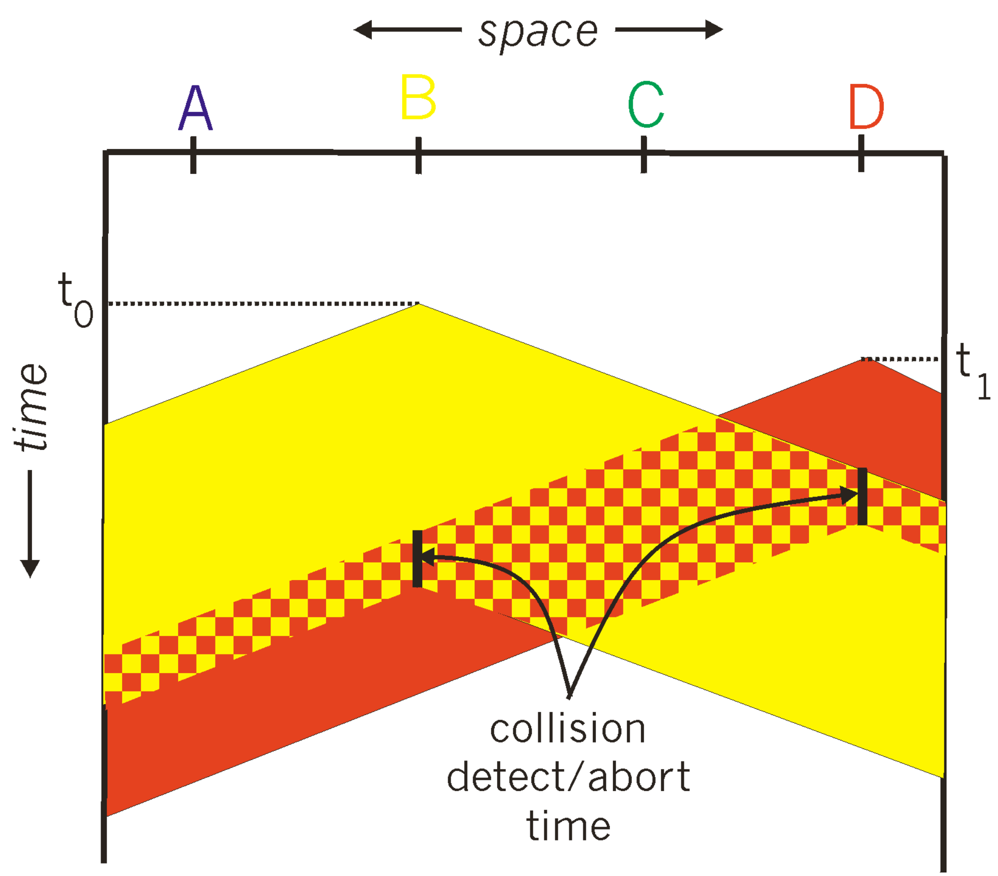
Multiple Access Protocol

- Single shared broadcast channel
  - Avoid having multiple nodes speaking at once
  - Otherwise, collisions lead to garbled data
- Multiple access protocol
  - Distributed algorithm for sharing the channel
  - Algorithm determines which node can transmit
- Classes of techniques
  - Channel partitioning: divide channel into pieces
    - Time-division multiplexing, frequency division multiplexing
  - Taking turns: passing a token for right to transmit
  - Random access: allow collisions, and then recover

Key Ideas of Random Access

- Carrier Sense (CS)
  - *Listen before speaking, and don't interrupt*
  - Checking if someone else is already sending data
  - … and waiting till the other node is done
- Collision Detection (CD)
  - *If someone else starts talking at the same time, stop*
  - Realizing when two nodes are transmitting at once
  - …by detecting that the data on the wire is garbled
- Randomness
  - *Don't start talking again right away*
  - Waiting for a random time before trying again

CSMA/CD Collision Detection



Wireless: Avoidance, Not Detection

- Collision detection in wired Ethernet
  - Station listens while transmitting
  - Detects collision with other transmission
  - Aborts transmission and tries sending again
- Problem #1: cannot detect all collisions
  - Hidden terminal problem
  - Fading
- Problem #2: listening while sending
  - Strength of received signal is much smaller
  - Expensive to build hardware that detects collisions
- So, 802.11 does *not* do collision detection

Medium Access Control in 802.11

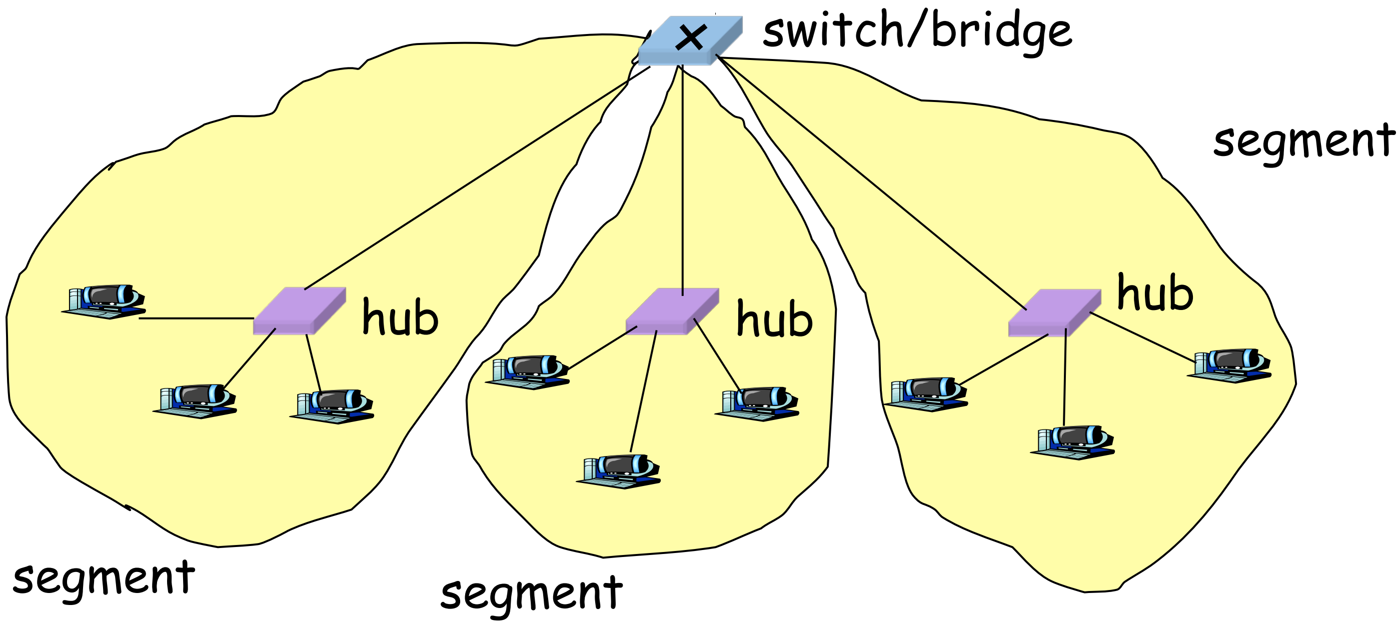
- Collision avoidance, not detection
  - First exchange control frames before transmitting data
    - Sender issues “Request to Send” (RTS), including length of data
    - Receiver responds with “Clear to Send” (CTS)
  - If sender sees CTS, transmits data (of specified length)
  - If other node sees CTS, will idle for specified period
  - If other node sees RTS but not CTS, free to send
- Link-layer acknowledgment and retransmission
  - CRC to detect errors
  - Receiving station sends an acknowledgment
  - Sending station retransmits if no ACK is received
  - Giving up after a few failed transmissions

Scaling the Link Layer

- Ethernet traditionally limited by fading signal strength in long wires
  - Introduction of hubs/repeaters to rebroadcast
- Still a maximum "length" for a Ethernet segment
  - Otherwise, two nodes might be too far for carrier sense to detect concurrent broadcasts
- Further, too many nodes in shorter Ethernet can yield low transmissions rates
  - Constantly conflict with one another

Bridges/Switches: Traffic Isolation

- Switch breaks subnet into LAN segments
- Switch filters packets
  - Frame only forwarded to the necessary segments
  - Segments can support separate transmissions

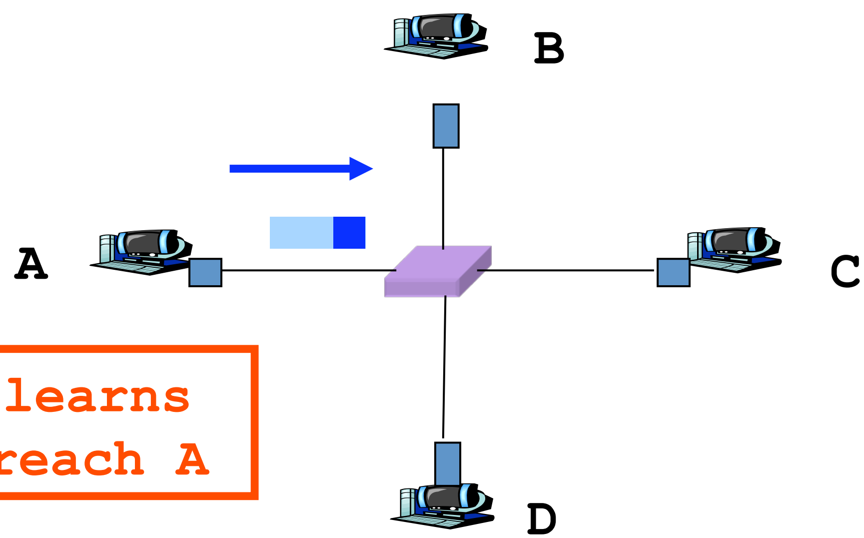


Comparing Hubs, Switches, Routers

	Hub/ Repeater	Bridge/ Switch	Router
Traffic isolation	no	yes	yes
Plug and Play	yes	yes	no
Efficient routing	no	no	yes
Cut through	yes	yes	no

Self Learning: Building the Table

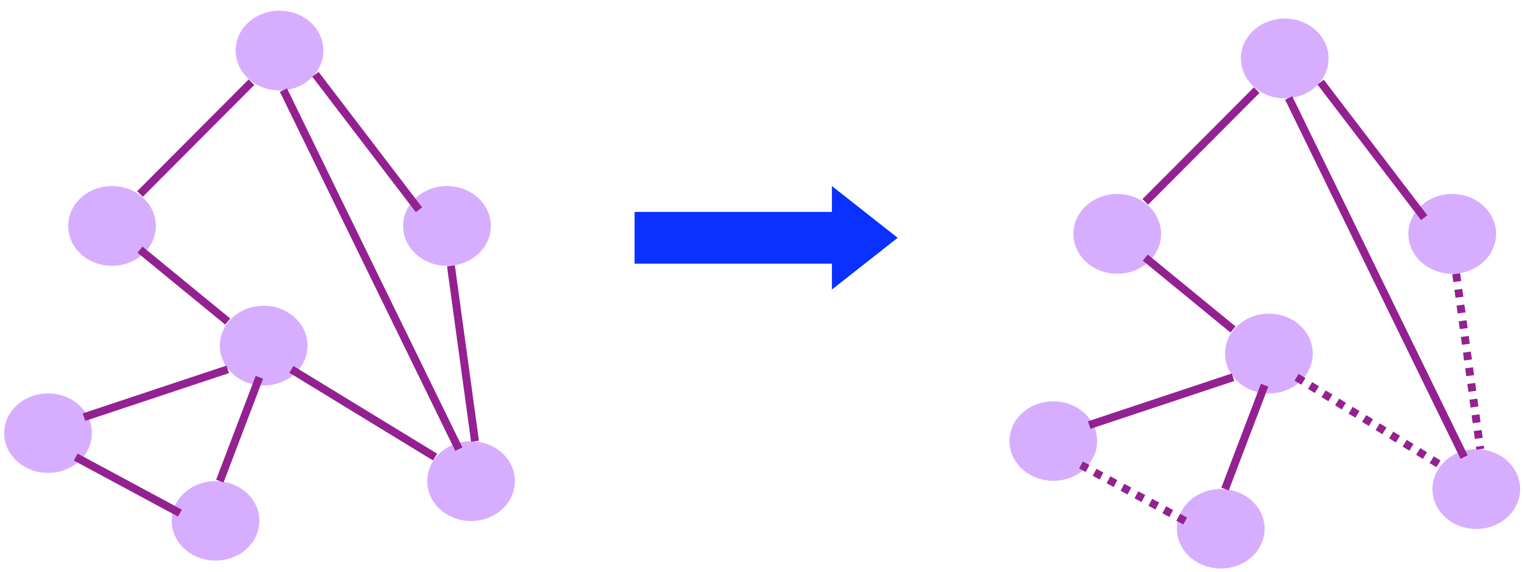
- When a frame arrives
  - Inspect the *source* MAC address
  - Associate the address with the *incoming* interface
  - Store the mapping in the switch table
  - Use a time-to-live field to eventually forget the mapping



Switch learns how to reach A

Solution: Spanning Trees

- Ensure the topology has no loops
  - Avoid using some of the links when flooding
  - … to avoid forming a loop
- Spanning tree
  - Sub-graph that covers all vertices but contains no cycles
  - Links not in the spanning tree do not forward frames

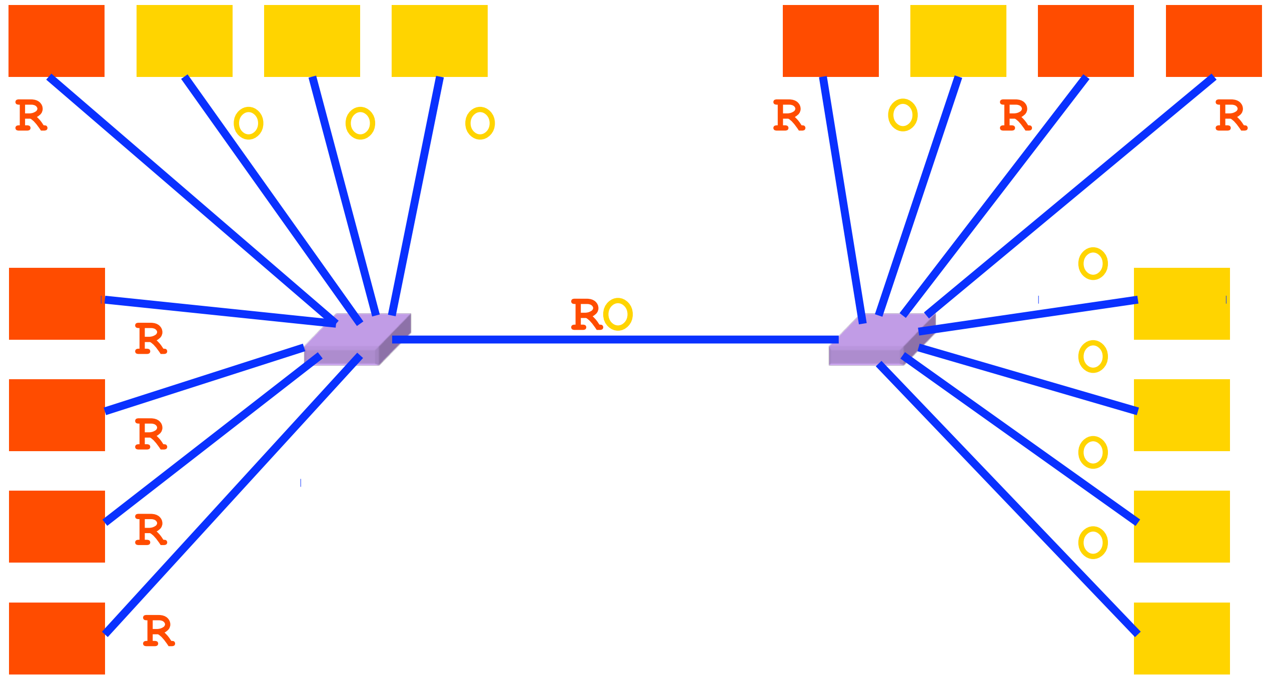


Evolution Toward Virtual LANs

- In the olden days…
  - Thick cables snaked through cable ducts in buildings
  - Every computer they passed was plugged in
  - All people in adjacent offices were put on the same LAN
  - Independent of whether they belonged together or not
- More recently…
  - Hubs and switches changed all that
  - Every office connected to central wiring closets
  - Often multiple LANs (*k* hubs) connected by switches
  - Flexibility in mapping offices to different LANs

Group users based on organizational structure, rather than the physical layout of the building.

Example: Two Virtual LANs



Red VLAN and Orange VLAN

Switches forward traffic as needed

Network Layer

IP Packet Structure

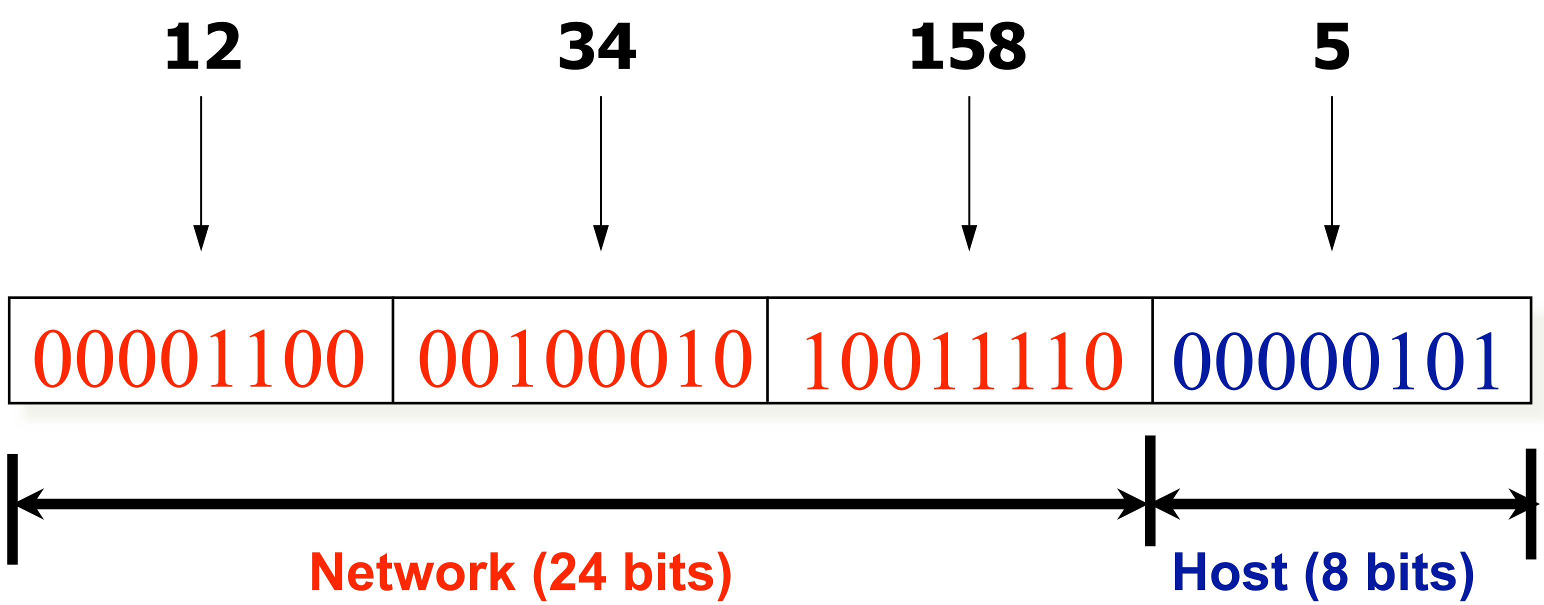
<table>
<tr><td>4-bit Version</td><td>4-bit Header Length</td><td colspan="2">8-bit Type of Service (TOS)</td><td colspan="4">16-bit Total Length (Bytes)</td></tr>
<tr><td colspan="4">16-bit Identification</td><td>3-bit Flags</td><td colspan="3">13-bit Fragment Offset</td></tr>
<tr><td colspan="2">8-bit Time to Live (TTL)</td><td colspan="2">8-bit Protocol</td><td colspan="4">16-bit Header Checksum</td></tr>
<tr><td colspan="8">32-bit Source IP Address</td></tr>
<tr><td colspan="8">32-bit Destination IP Address</td></tr>
<tr><td colspan="8">Options (if any)</td></tr>
<tr><td colspan="8">Payload</td></tr>
</table>

Source Address: What if Source Lies?

- Source address should be the sending host
  - But, who's checking, anyway?
  - You could send packets with any source you want
- Why would someone want to do this?
  - Launch a denial-of-service attack
    - Send excessive packets to the destination
    - … to overload the node, or the links leading to node
  - Evade detection by "spoofing"
    - But, the victim could identify you by the source address
    - So, you can put someone else's source address in packets
  - Also, an attack against the spoofed host
    - Spoofed host is wrongly blamed
    - Spoofed host may receive return traffic from receiver

Hierarchical Addressing: IP Prefixes

- IP addresses can be divided into two portions
  - Network (left) and host (right)
- 12.34.158.0/24 is a 24-bit **prefix**
  - Which covers 2^8 addresses (e.g., up to 255 hosts)

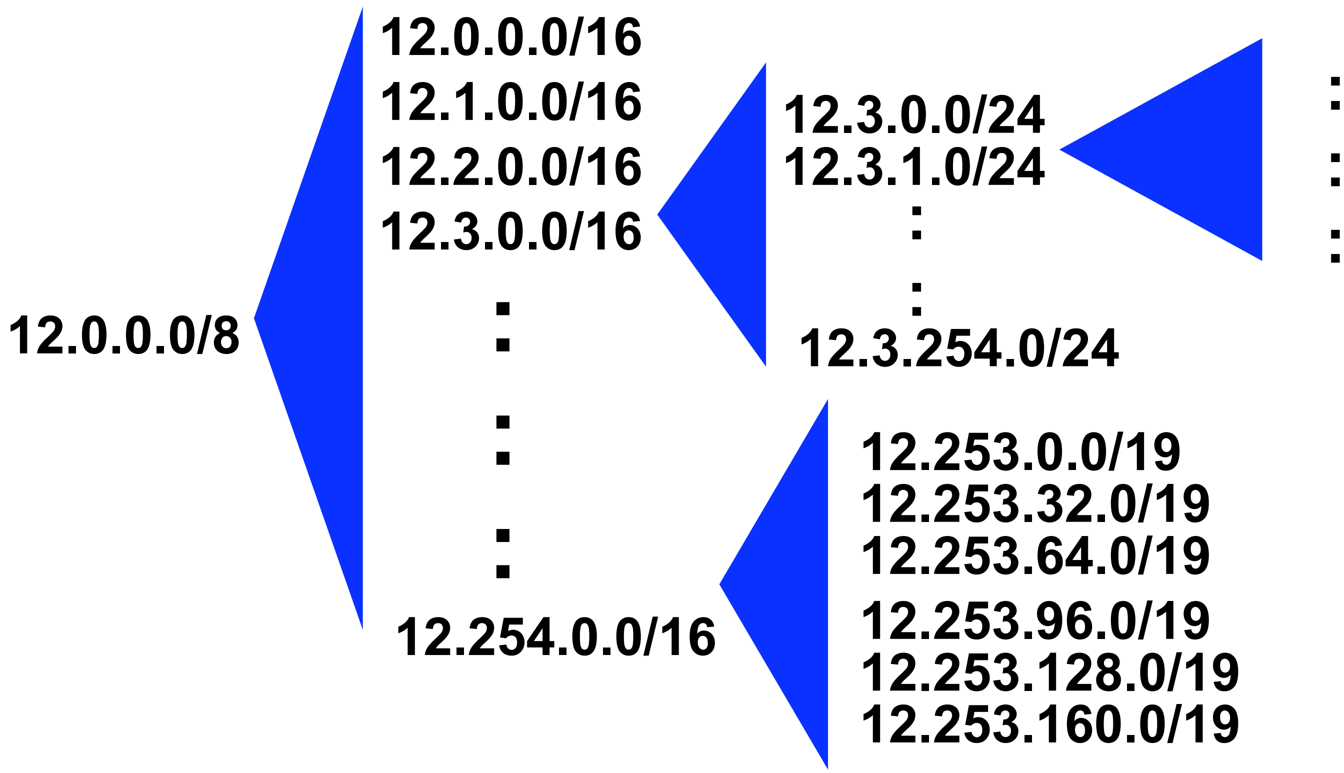


Classful Addressing

- In the olden days, only fixed allocation sizes
  - Class A: 0*
    - Very large /8 blocks (e.g., MIT has 18.0.0.0/8)
  - Class B: 10*
    - Large /16 blocks (e.g,. Princeton has 128.112.0.0/16)
  - Class C: 110*
    - Small /24 blocks (e.g., AT&T Labs has 192.20.225.0/24)
  - Class D: 1110*
    - Multicast groups
  - Class E: 11110*
    - Reserved for future use
- This is why folks use dotted-quad notation!

CIDR: Hierarchal Address Allocation

- Prefixes are key to Internet scalability
  - Address allocated in contiguous chunks (prefixes)
  - Routing protocols and packet forwarding based on prefixes
  - Today, routing tables contain ~200,000 prefixes (vs. 4B)

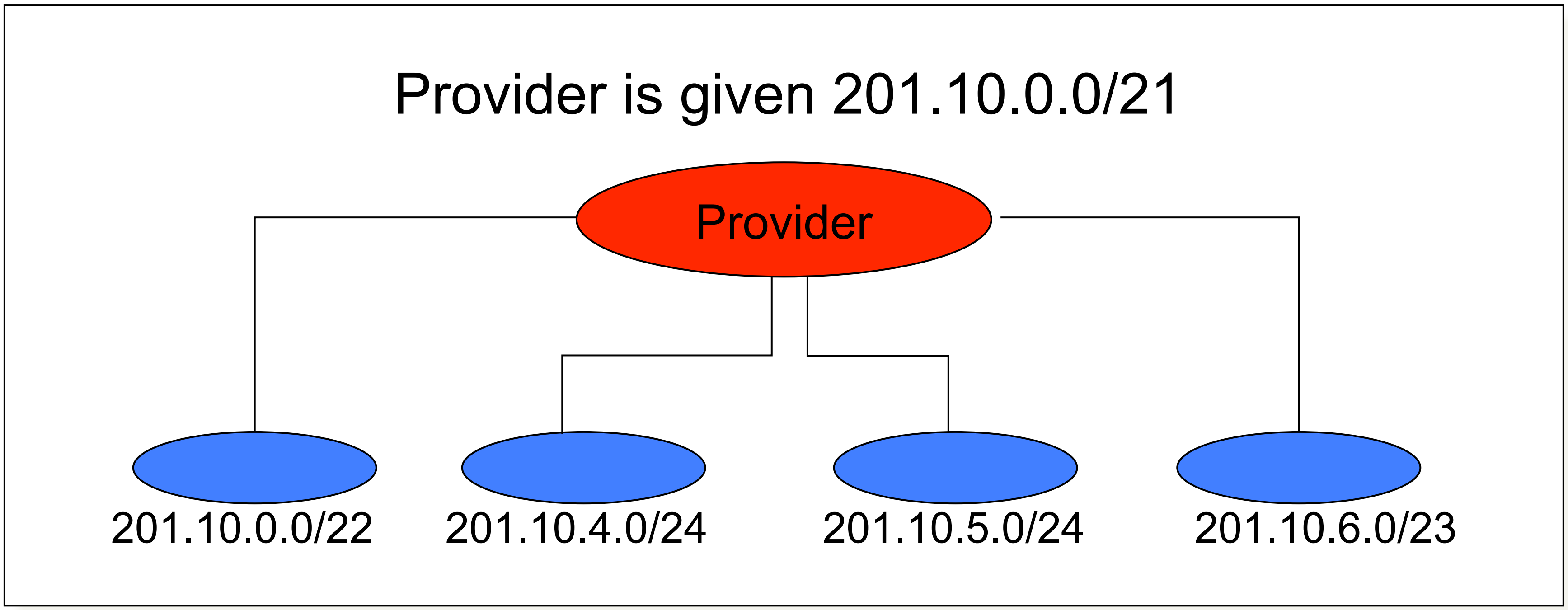


Two types of addresses

- Provider independent (from IANA)
- Provider allocated (from upstream ISP)

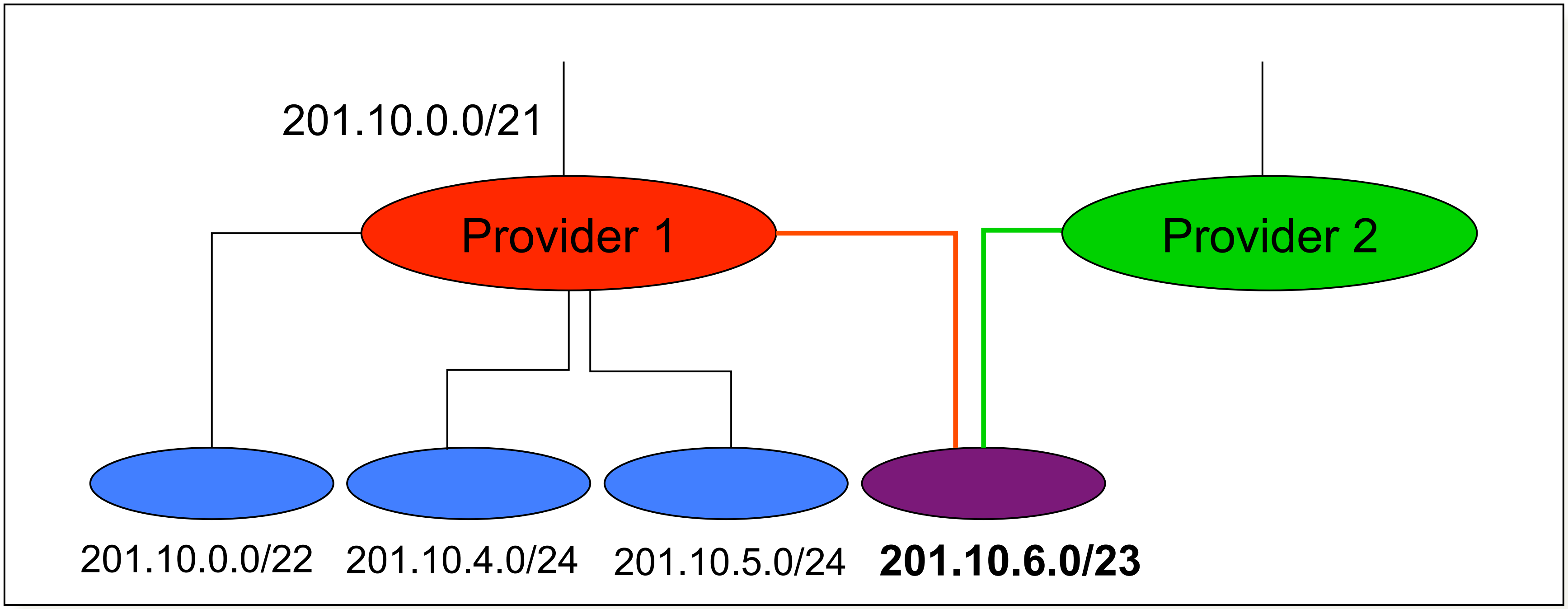
- Provider allocated addresses seem to offer more potential for aggregation (and reducing routing table size), but not always so…

Scalability: Address Aggregation



Routers in rest of Internet just need to know how to reach 201.10.0.0/21. Provider can direct IP packets to appropriate customer.

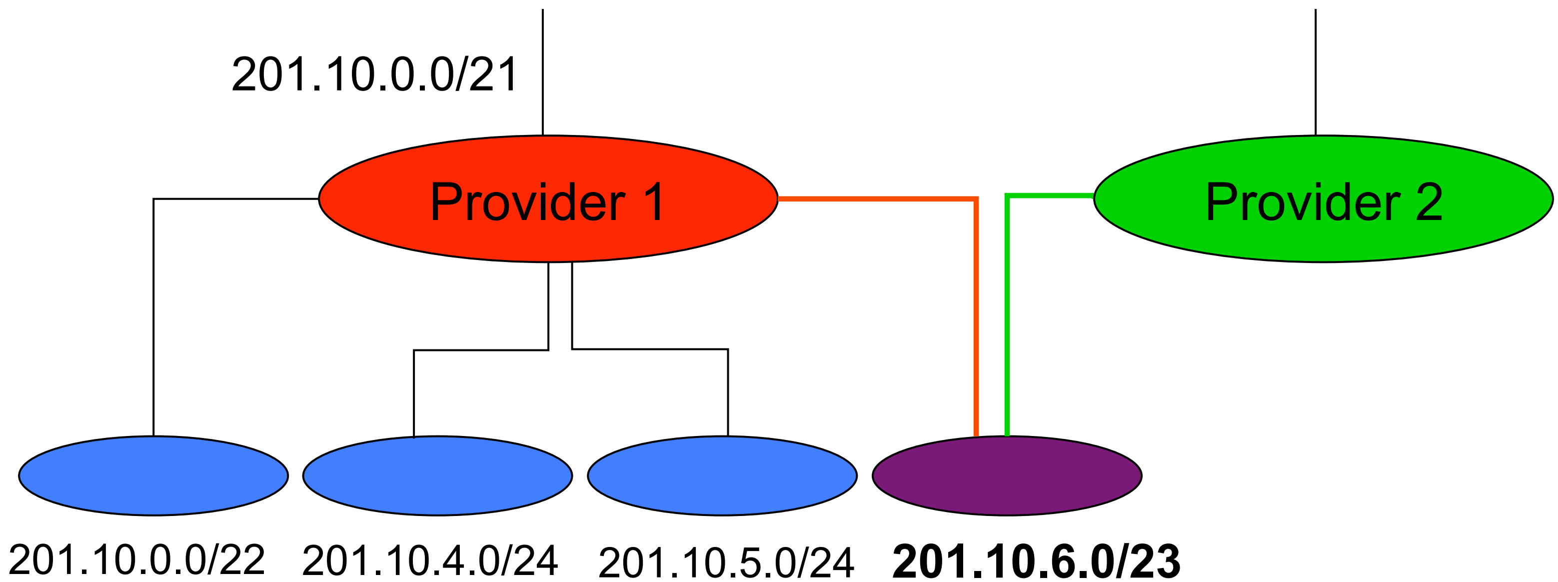
But, Aggregation Not Always Possible



Multi-homed customer (201.10.6.0/23) has two providers. Other parts of the Internet need to know how to reach these destinations through *both* providers.

CIDR Makes Packet Forwarding Harder

- Forwarding table may have many matches
  - E.g., entries for 201.10.0.0/21 and 201.10.6.0/23
  - The IP address 201.10.6.17 would match *both*!
  - Use Longest Prefix Matching
- Can lead to routing table expansion
  - To satify LPM, need to announce /23 from both 1 and 2



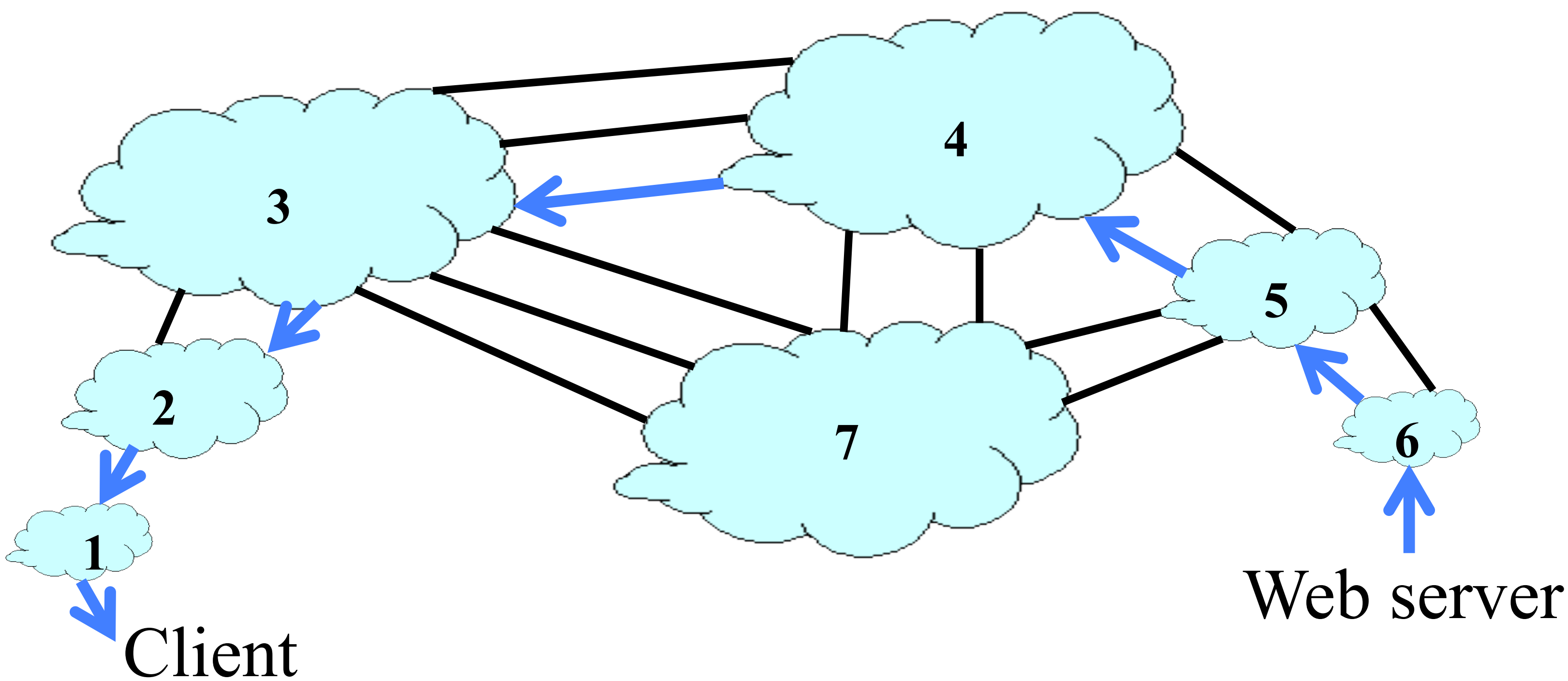
Two types of addresses

- Provider independent (from IANA)
- Provider allocated (from upstream ISP)

- Provider allocated addresses seem to offer more potential for aggregation (and reducing routing table size), but not always so…
  - Multi-homing a PA address
  - Traffic engineering between multiple links to same single provider

Internet-wide Internet Routing

- AS-level topology
  - Destinations are IP prefixes (e.g., 12.0.0.0/8)
  - Nodes are Autonomous Systems (ASes)
  - Edges are links and business relationships



Intradomain routing
(Interior Gateway Protocol – IGP)

Link-state:

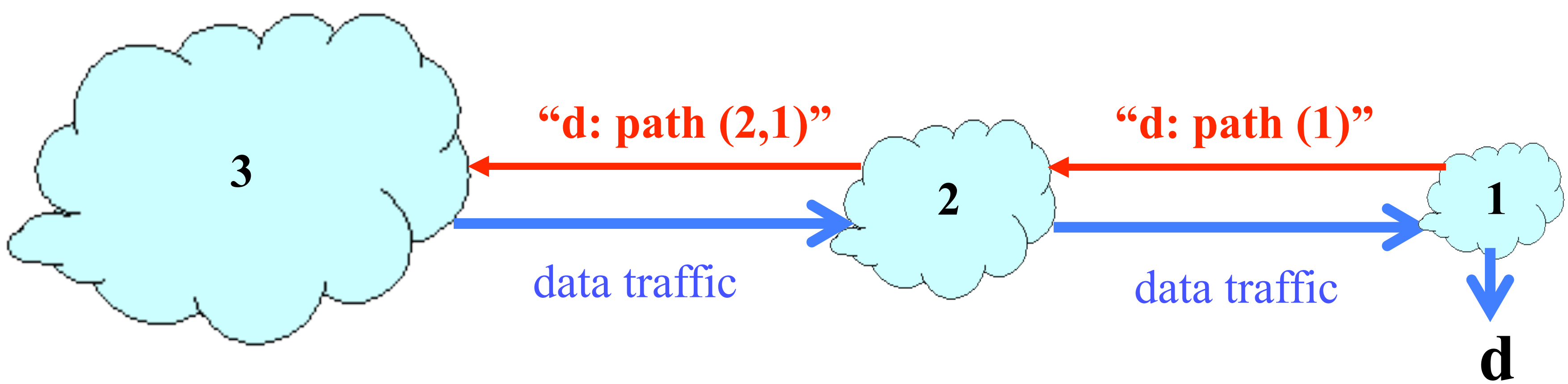
- Keep complete map of all links
- Fast convergence
- Node can advertise incorrect *link* cost
- Each node computes only its *own* table
- OSPF, IS-IS, …

Distance Vector:

- Keep only next-hop and cost information for each destination
- Convergence time varies (can be loops, count-to-infinity)
- DV node can advertise incorrect *path* cost
- Each node's table used by others (error propagates)
- RIP, …

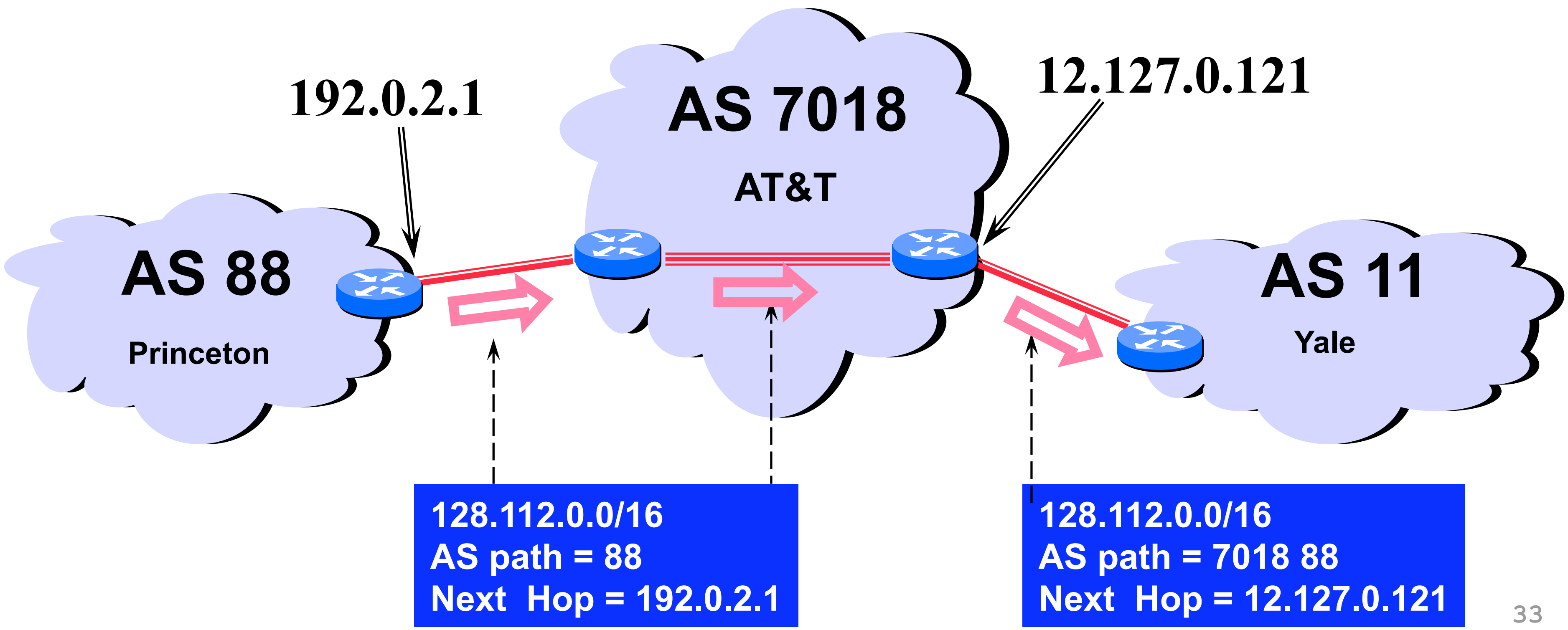
Path-Vector Routing

- Extension of distance-vector routing
  - Support flexible routing policies
  - Avoid count-to-infinity problem
- 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 Route

- Destination prefix (e.g., 128.112.0.0/16)
- Route attributes, including
  - AS path (e.g., “7018 88”)
  - Next-hop IP address (e.g., 12.127.0.121)



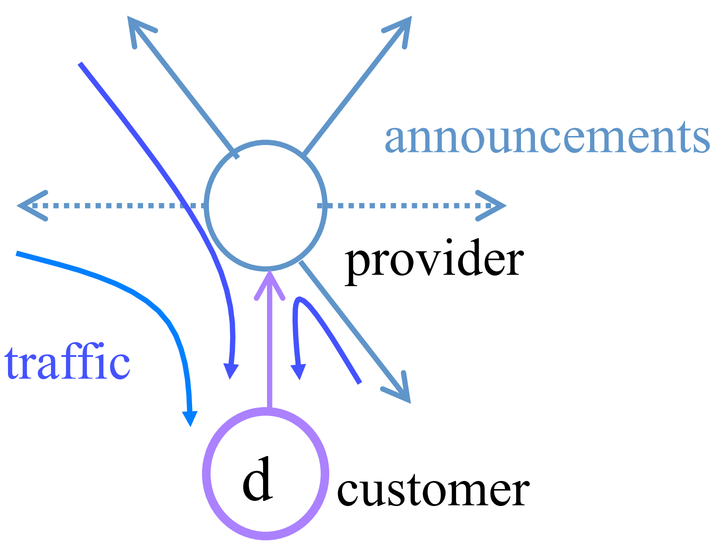
BGP Policy: Applying Policy to Routes

- Import policy
  - Filter unwanted routes from neighbor
    - E.g. prefix that your customer doesn't own
  - Manipulate attributes to influence path selection
    - E.g., assign local preference to favored routes
- Export policy
  - Filter routes you don't want to tell your neighbor
    - E.g., don't tell a peer a route learned from other peer
  - Manipulate attributes to control what they see
    - E.g., make a path look artificially longer than it is

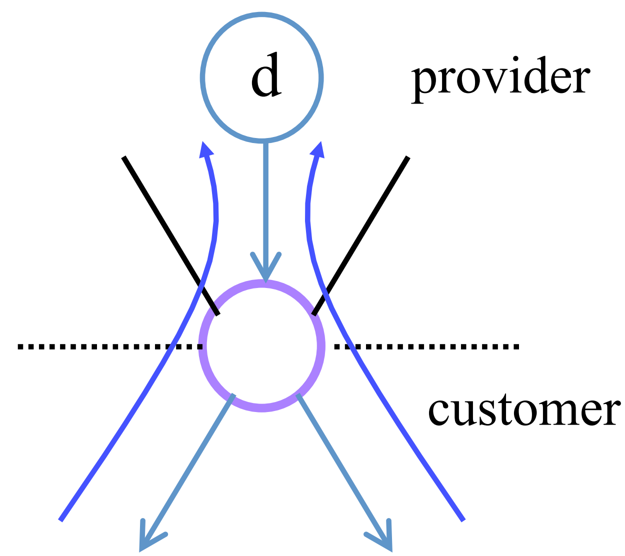
Customer-Provider Relationship

- Customer needs to be reachable from everyone
  - Provider tells all neighbors how to reach the customer
- Customer does not want to provide transit service
  - Customer does not let its providers route through it

Traffic **to** the customer



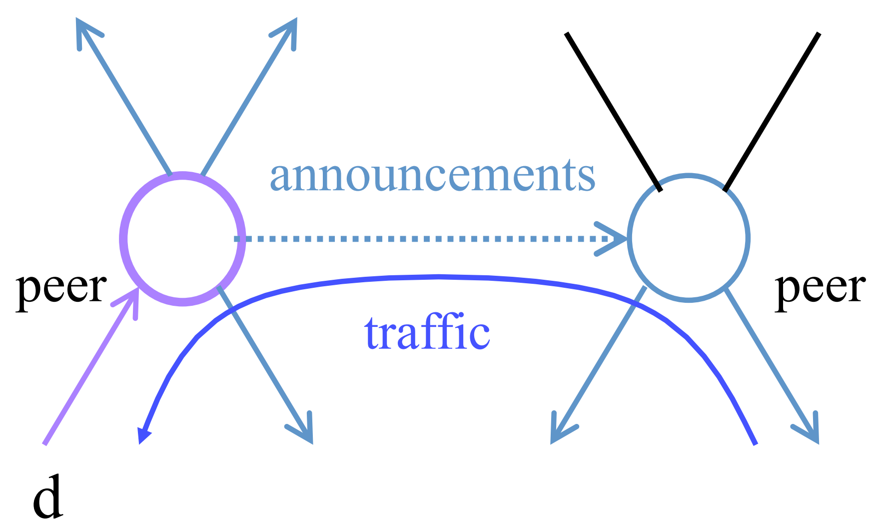
Traffic **from** the customer



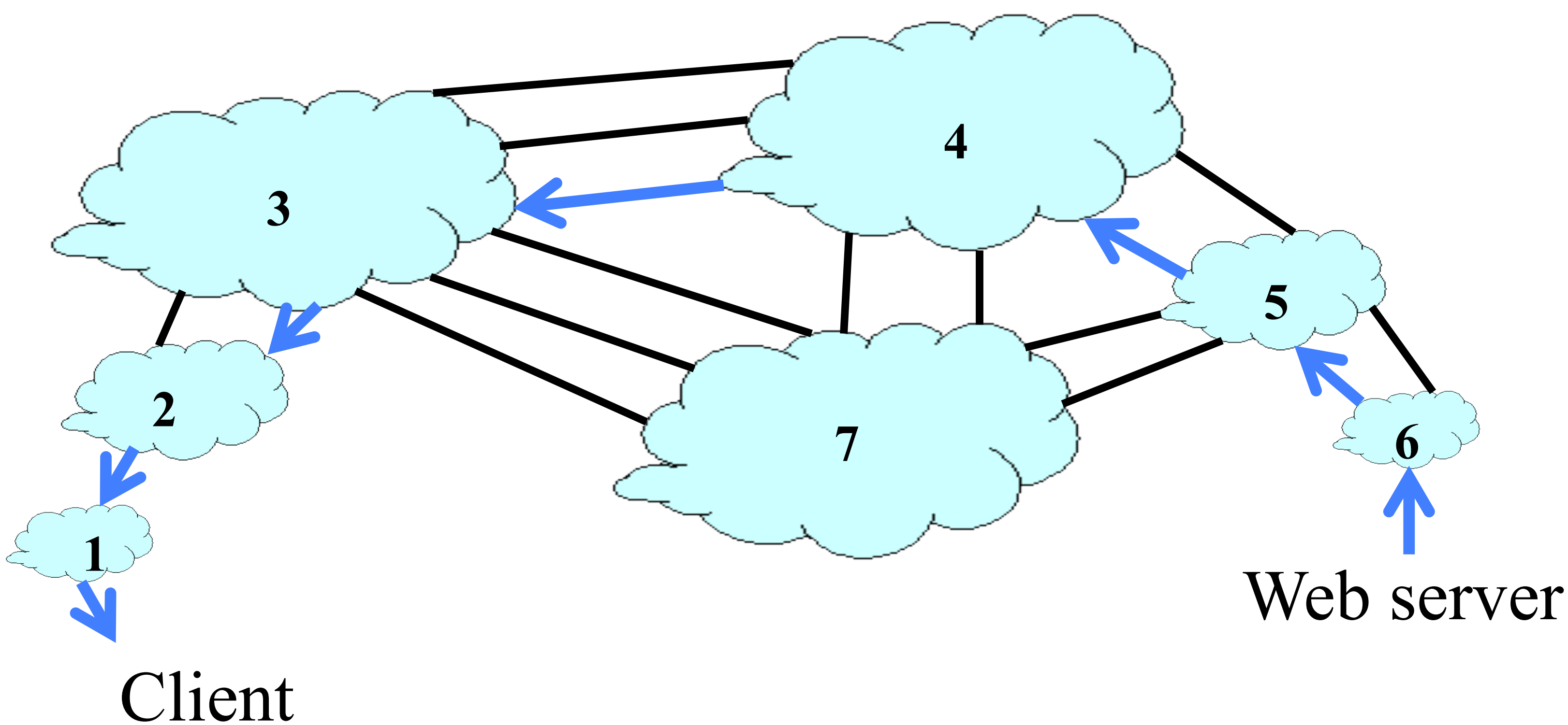
Peer-Peer Relationship

- Peers exchange traffic between customers
  - AS exports *only* customer routes to a peer
  - AS exports a peer's routes *only* to its customers
  - Often the relationship is settlement-free (i.e., no $$$)

Traffic to/from the peer and its customers



Identify the peer/transit links!



Extending the network layer

- Anycast
- Multicast
- Middleboxes

Motivation for IP anycast

- Failure problem: client has resolved IP address
  – What if IP address can represent many servers?

- Load-balancing/failover via IP addr, rather than DNS

- IP anycast is simple reuse of existing protocols
  – Multiple instances of a service share same IP address
  – Each instance announces IP address / prefix in BGP / IGP
  – Routing infrastructure directs packets to nearest instance of the service
    - Can use same selection criteria as installing routes in the FIB
  – No special capabilities in servers, clients, or network

Downsides of IP anycast

- Many Tier-1 ISPs ingress filter prefixes > /24
  - Publish a /24 to get a "single" anycasted address: Poor utilization
- Scales poorly with the # anycast groups
  - Each group needs entry in global routing table
- Not trivial to deploy
  - Obtain an IP prefix and AS number; speak BGP
- Subject to the limitations of IP routing
  - No notion of load or other application-layer metrics
  - Convergence time can be slow (as BGP or IGP convergence)
- Failover doesn't really work with TCP
  - TCP is stateful; other server instances will just respond with RSTs
  - Anycast may react to network changes, even though server online
- Root name servers (UDP) are anycasted, little else

IP Multicast

- Simple to use in applications
  - Multicast “group” defined by IP multicast address
    - IP multicast addresses look similar to IP unicast addrs
    - 224.0.0.0 to 239.255.255.255 (RPC 3171)
  - Best effort delivery only
    - Sender issues single datagram to IP multicast address
    - Routers delivery packets to all subnetworks that have a receiver “belonging” to the group
- Receiver-driven membership
  - Receivers join groups by informing upstream routers
  - Internet Group Management Protocol (v3: RFC 3376)

Middleboxes

- Middleboxes are intermediaries
  - Interposed in-between the communicating hosts
  - Often without knowledge of one or both parties
- Examples
  - Network address translators
  - Firewalls
  - Traffic shapers
  - Intrusion detection systems
  - Transparent Web proxy caches
  - Application accelerators

Two Views of Middleboxes

- An abomination
  - Violation of layering
  - Cause confusion in reasoning about the network
  - Responsible for many subtle bugs
- A practical necessity
  - Solving real and pressing problems
  - Needs that are not likely to go away

- Would they arise in *any* edge-empowered network, even if redesigned from scratch?

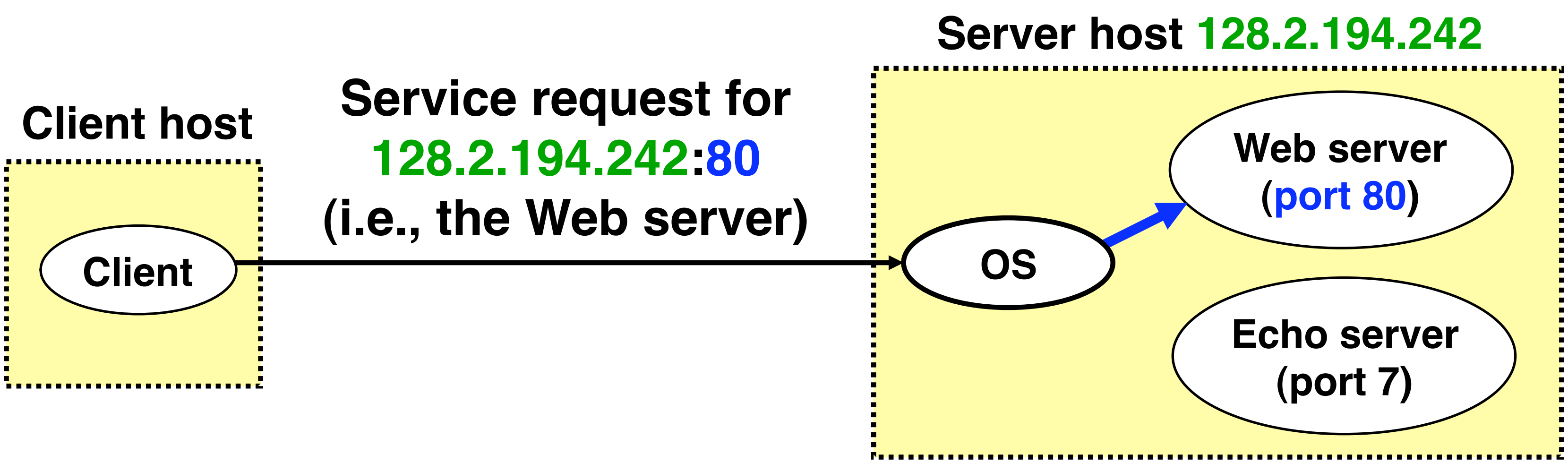
Port-Translating NAT

- Map outgoing packets
  - Replace source address with NAT address
  - Replace source port number with a new port number
  - Remote hosts respond using (NAT address, new port #)
- Maintain a translation table
  - Store map of (src addr, port #) to (NAT addr, new port #)
- Map incoming packets
  - Consult the translation table
  - Map the destination address and port number
  - Local host receives the incoming packet

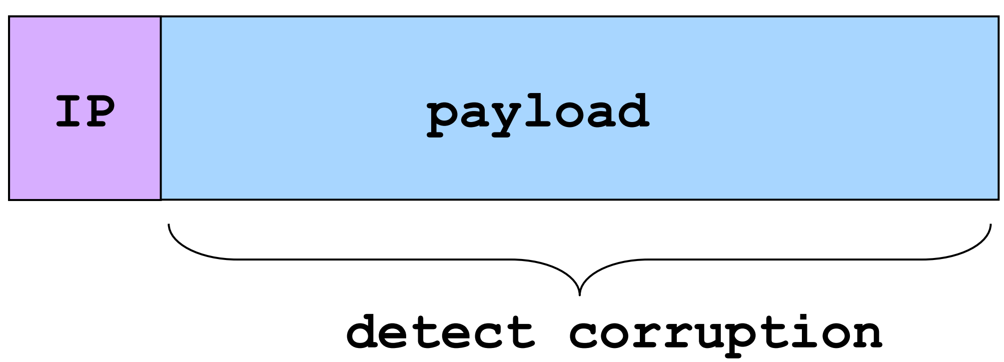
Transport Layer

Two Basic Transport Features

- **Demultiplexing:** port numbers

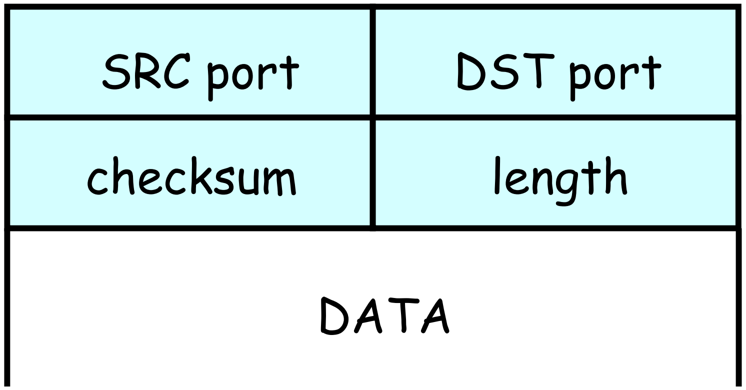


- **Error detection:** checksums



User Datagram Protocol (UDP)

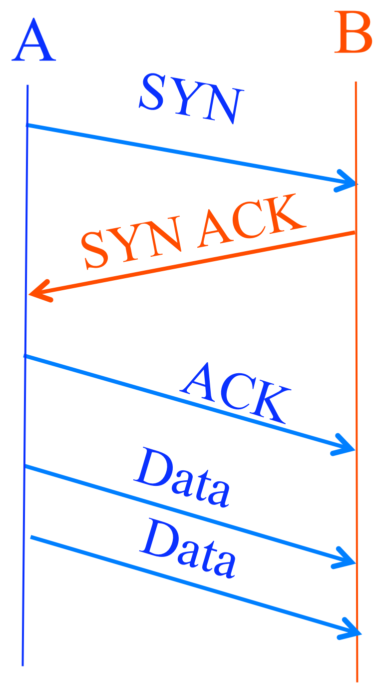
- Datagram messaging service
  - Demultiplexing of messages: port numbers
  - Detecting corrupted messages: checksum
- Lightweight communication between processes
  - Send messages to and receive them from a socket
  - Avoid overhead and delays of ordered, reliable delivery



Transmission Control Protocol (TCP)

- Stream-of-bytes service
  – Sends and receives a stream of bytes, not messages
- Reliable, in-order delivery
  – Checksums to detect corrupted data
  – Sequence numbers to detect losses and reorder data
  – Acknowledgments & retransmissions for reliable delivery
- Connection oriented
  – Explicit set-up and tear-down of TCP session
- Flow control
  – Prevent overflow of the receiver's buffer space
- Congestion control
  – Adapt to network congestion for the greater good

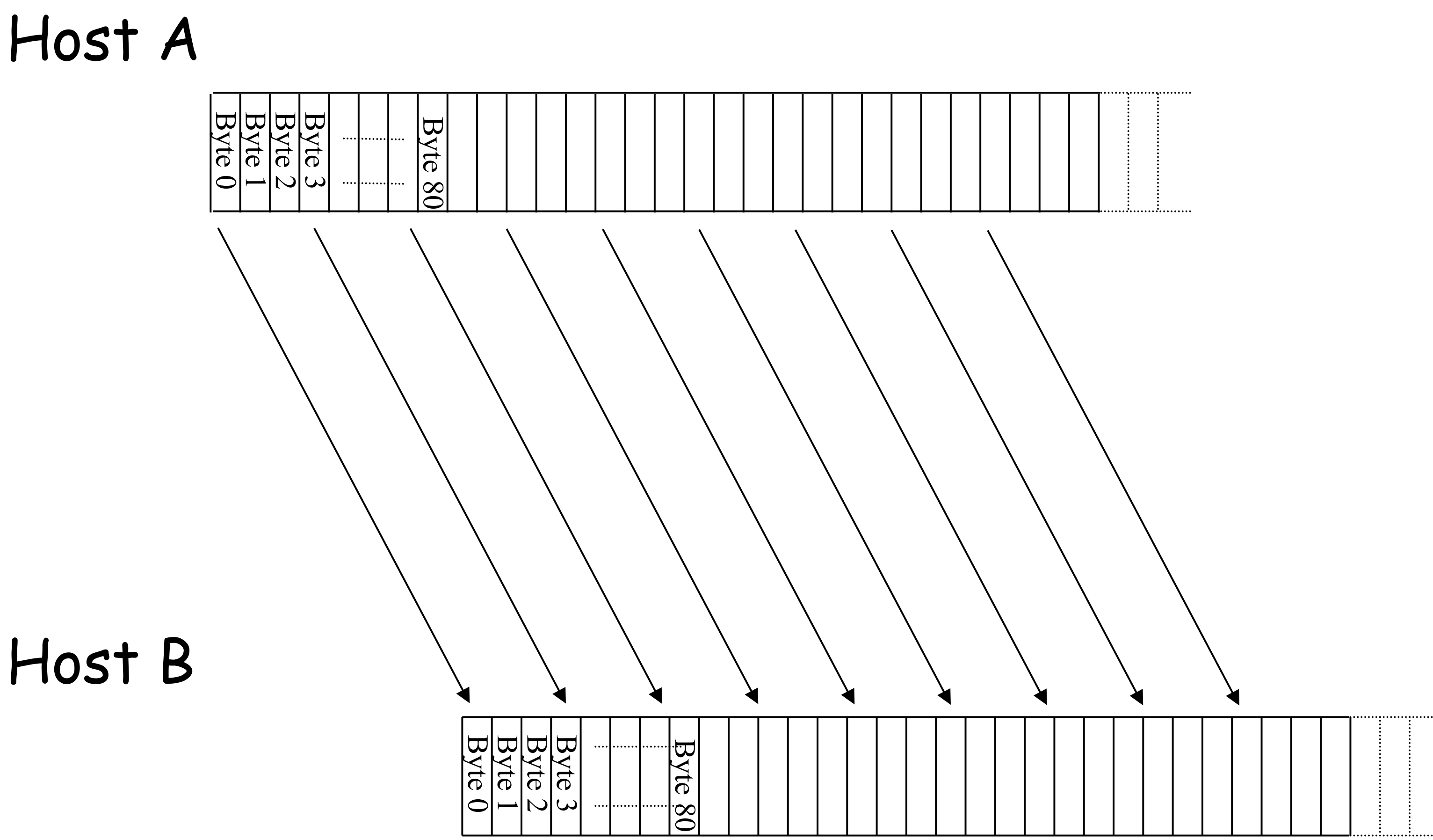
Establishing a TCP Connection



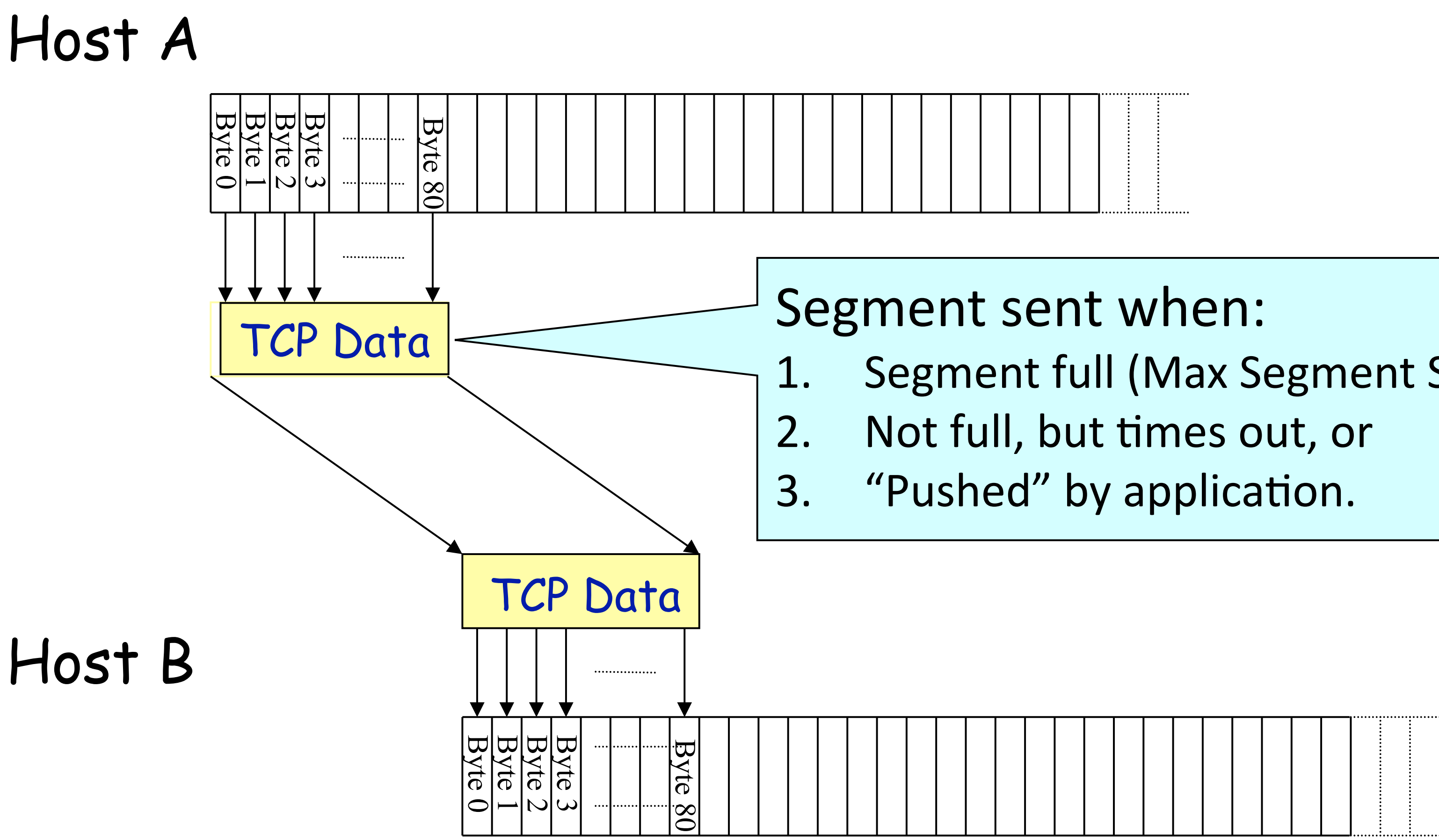
Each host tells its ISN to the other host.

- Three-way handshake to establish connection
  - Host A sends a **SYN**chronize (open) to the host B
  - Host B returns a SYN ACKnowledgment (**SYN ACK**)
  - Host A sends an **ACK** to acknowledge the SYN ACK

TCP "Stream of Bytes" Service



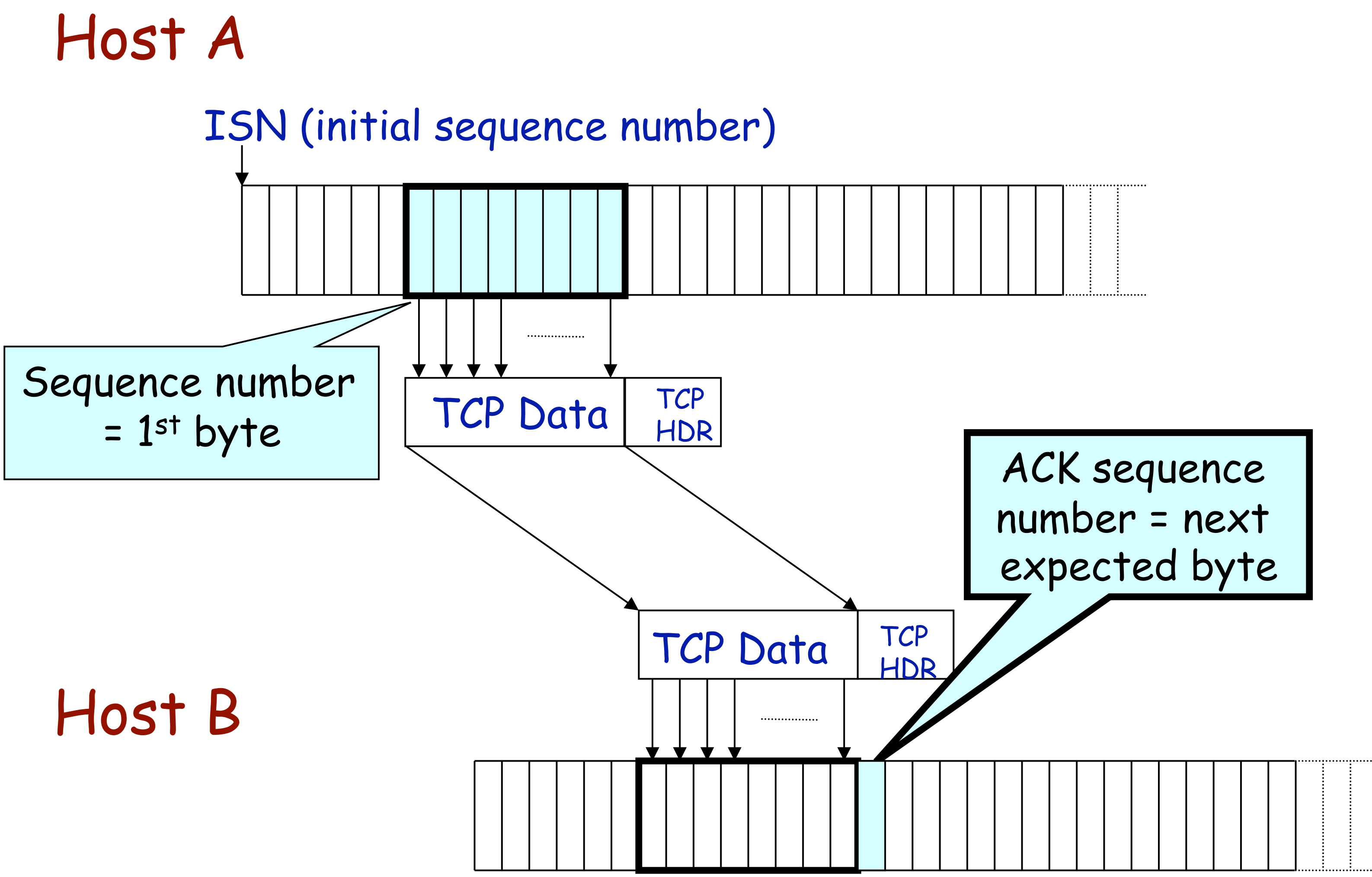
…Emulated Using TCP "Segments"



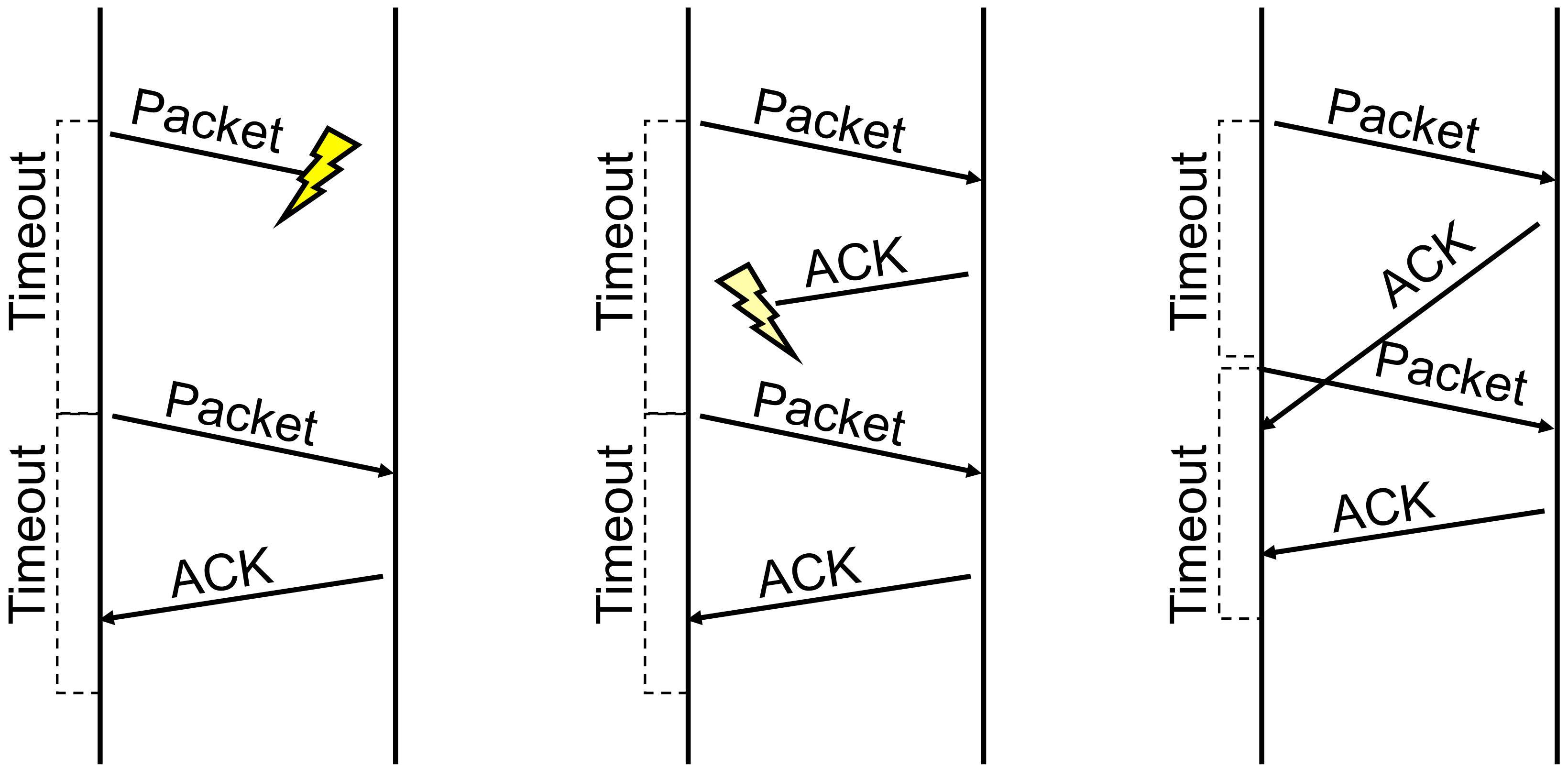
Segment sent when:

1. Segment full (Max Segment Size),
2. Not full, but times out, or
3. "Pushed" by application.

Reliability: TCP Acknowledgments



Detecting losses



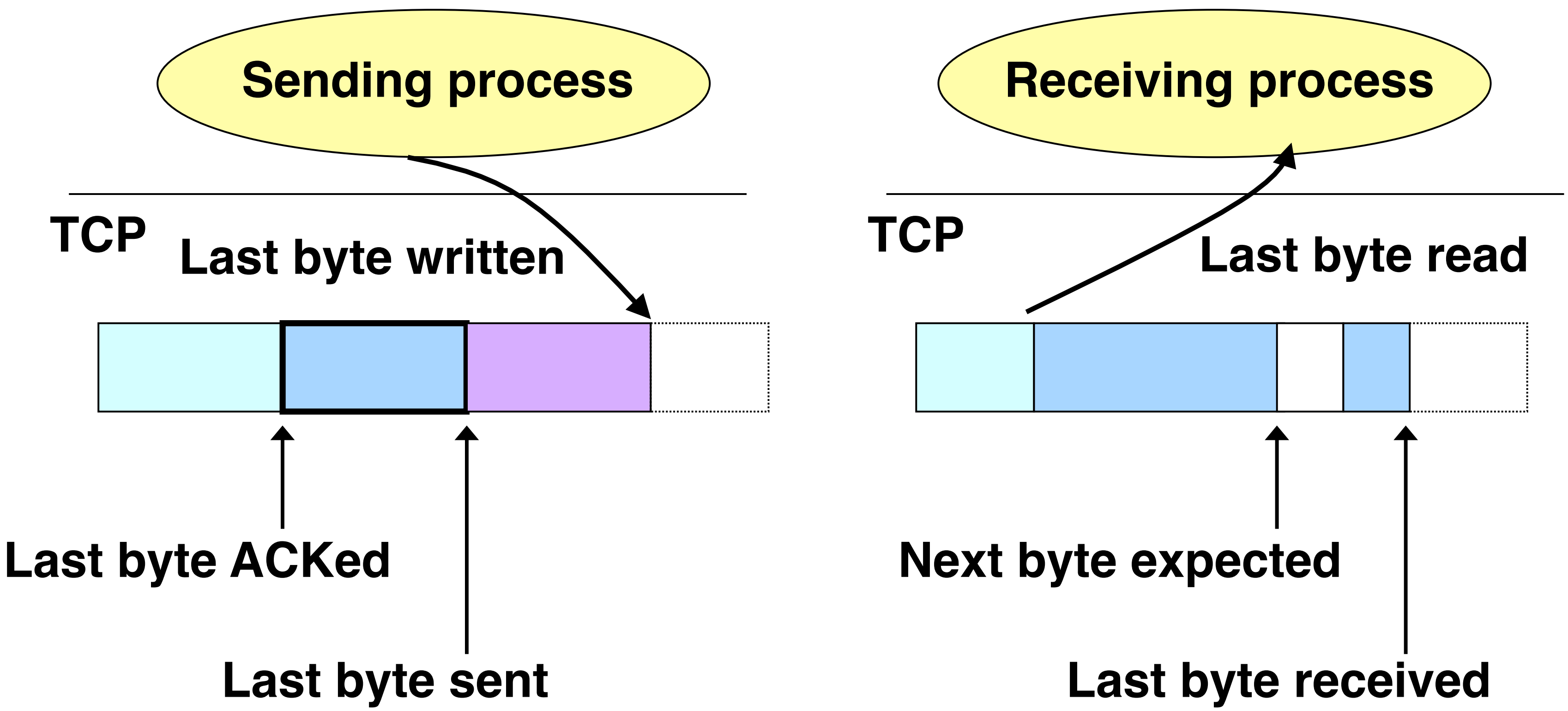
Packet lost

ACK lost
DUPLICATE PACKET

Early timeout
DUPLICATE PACKETS

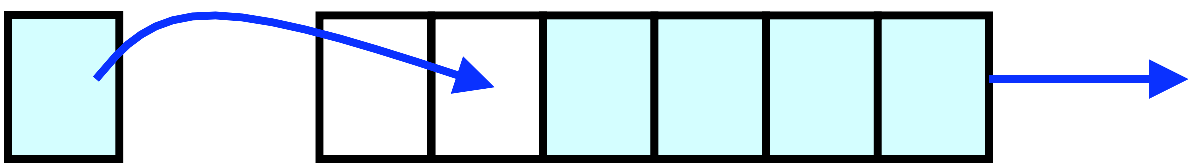
Flow control: Sliding window

- Allow a larger amount of data "in flight"
  - Allow sender to get ahead of the receiver
  - … though not *too far* ahead

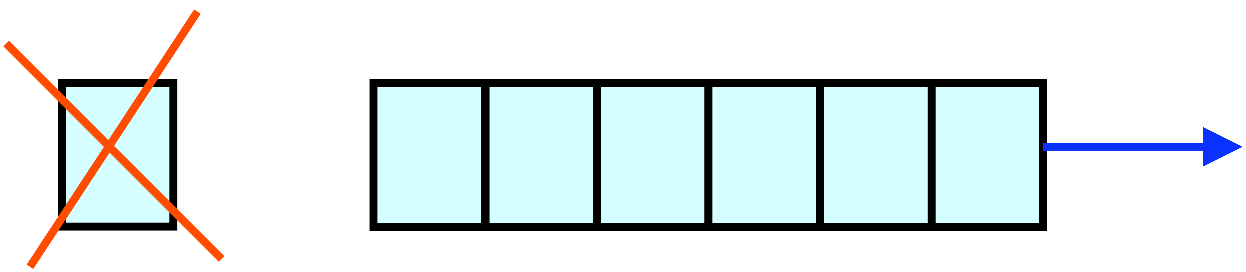


Where Congestion Happens: Links

- Simple resource allocation: FIFO queue & drop-tail
- Access to the bandwidth: first-in first-out queue
  - Packets transmitted in the order they arrive



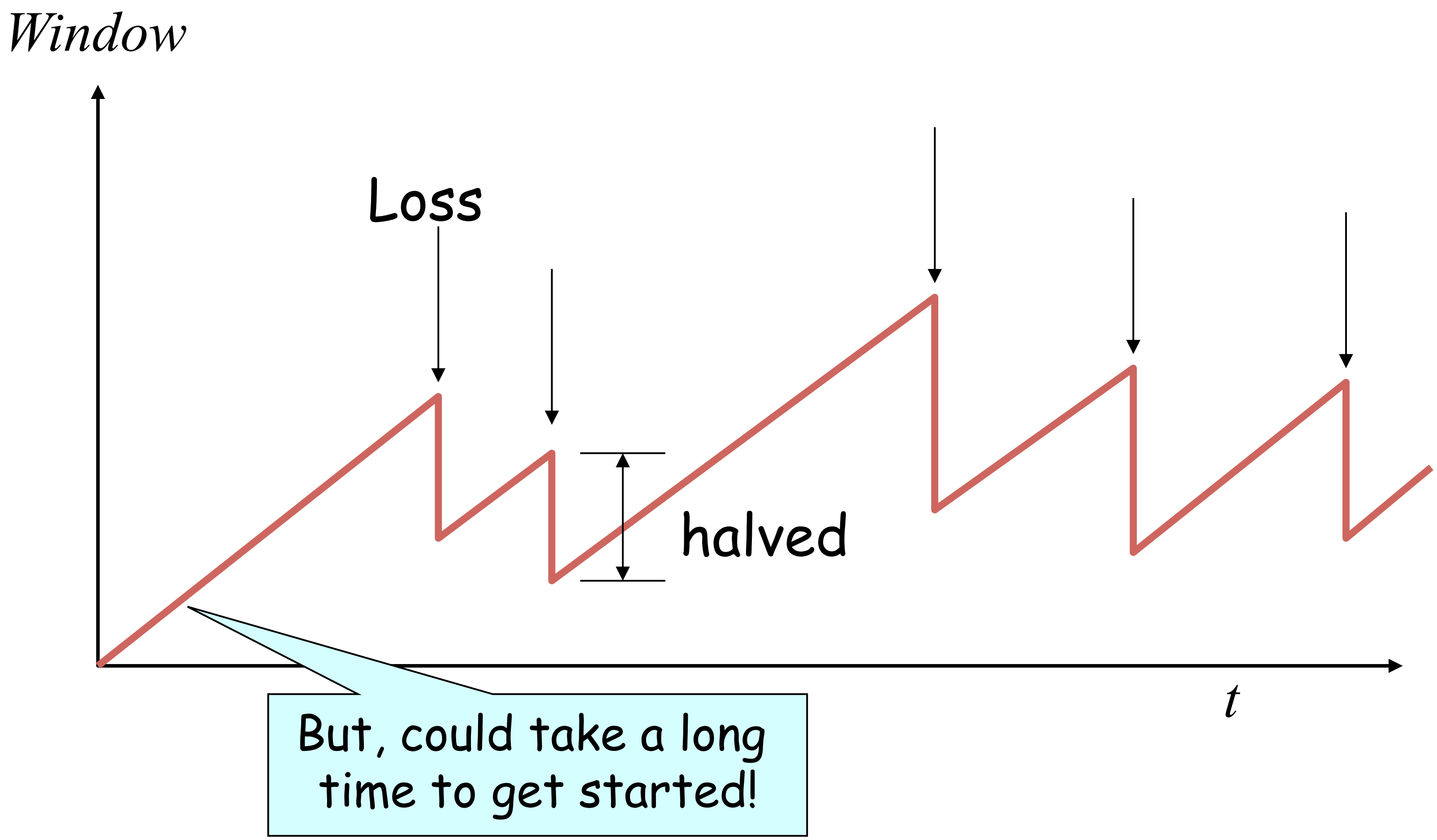
- Access to the buffer space: drop-tail queuing
  - If the queue is full, drop the incoming packet



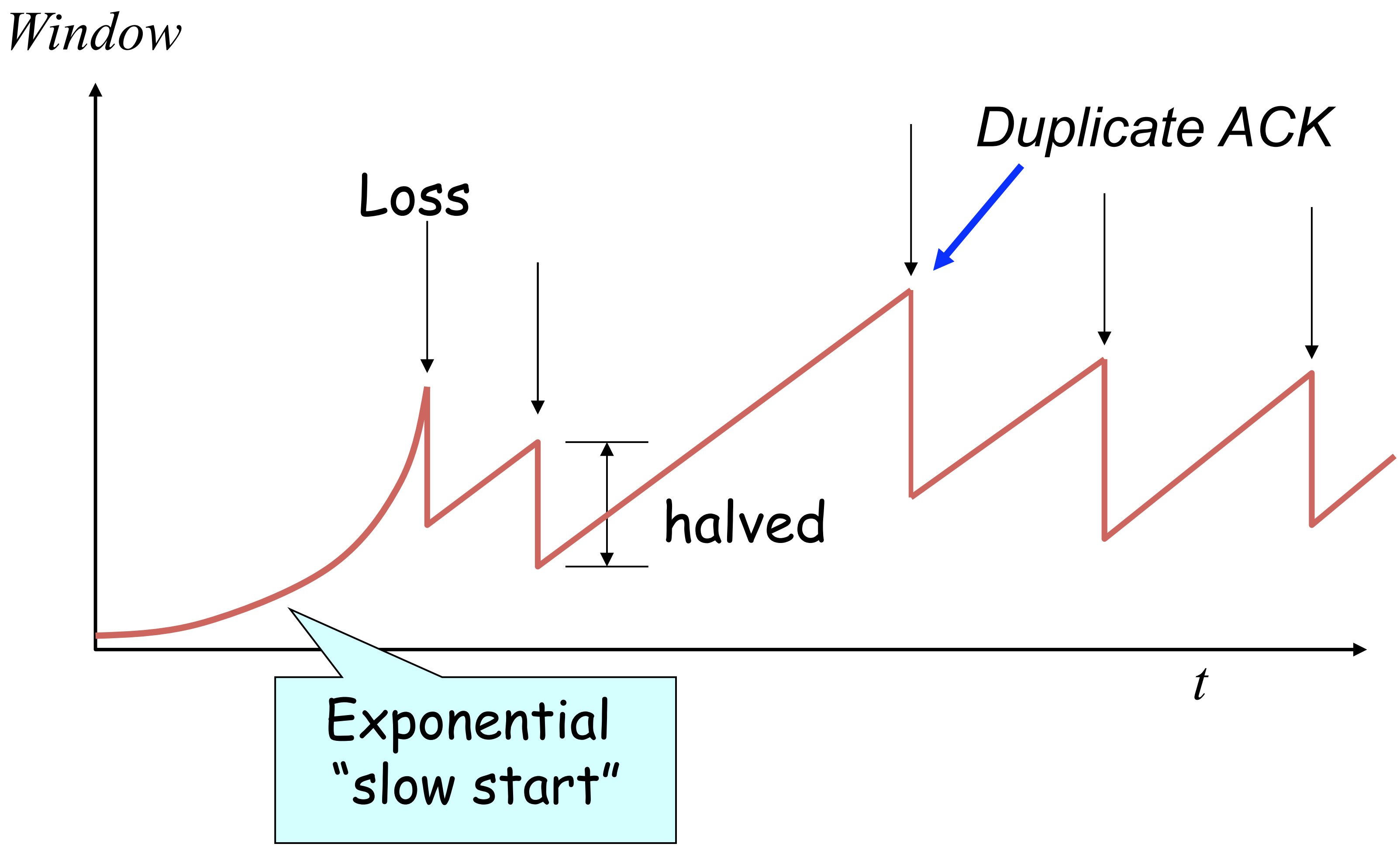
TCP Congestion Window

- Each TCP sender maintains a congestion window
  - Maximum number of bytes to have in transit
  - I.e., number of bytes still awaiting acknowledgments
- Adapting the congestion window
  - Decrease upon losing a packet: backing off
  - Increase upon success: optimistically exploring
  - Always struggling to find the right transfer rate
- Both good and bad
  - Pro: avoids having explicit feedback from network
  - Con: under-shooting and over-shooting the rate

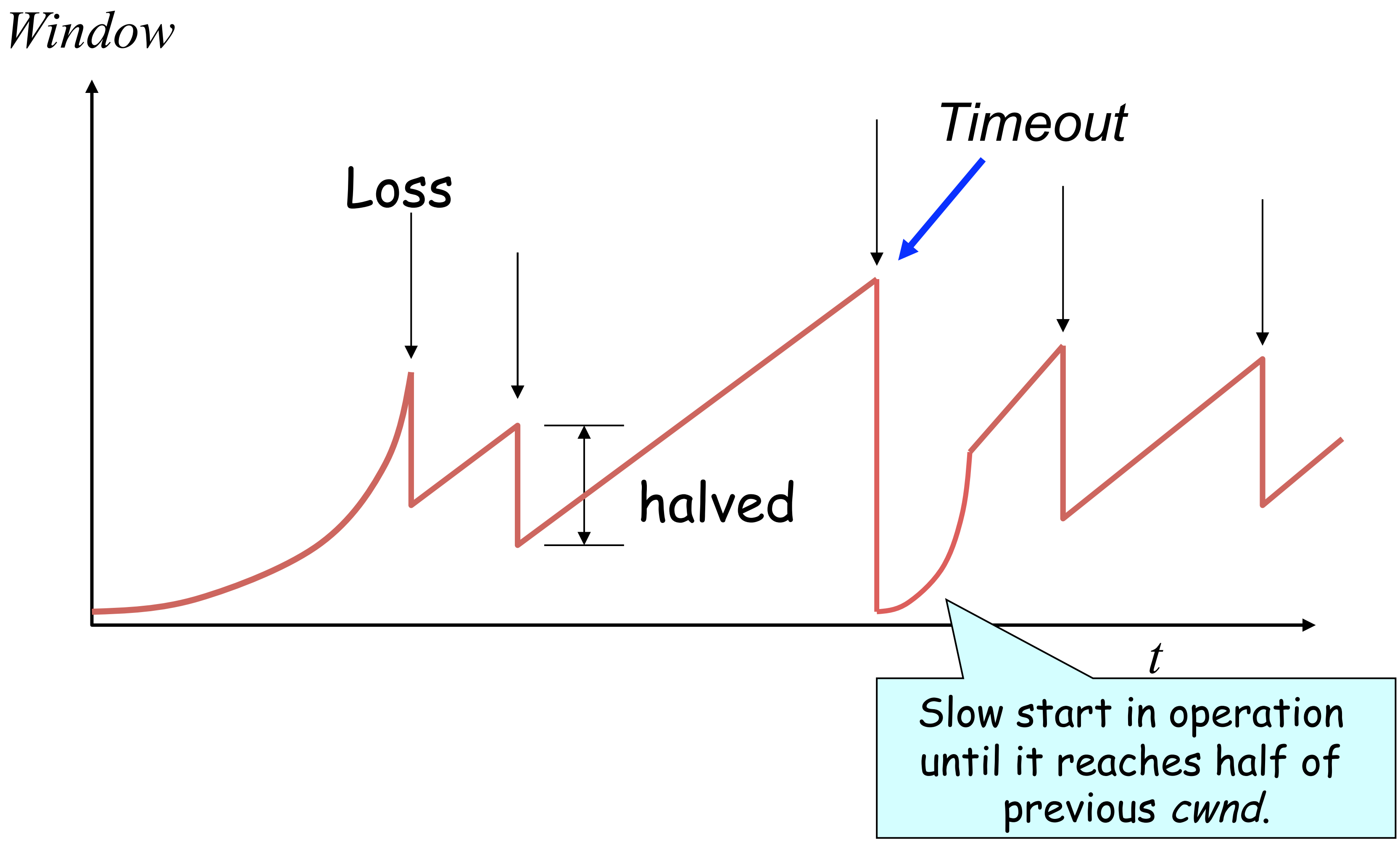
Leads to the TCP "Sawtooth"



Slow Start and the TCP Sawtooth



Repeating Slow Start After Timeout



Extensions

- Tail drop in routers lead to bursty loss and synchronization of senders
  - Led to Random Early Detection (RED)

- Packets dropped and retransmission when unnecessary
  - Led to Explicit Congestion Notification (ECN)

Application layer

DNS

HTTP and CDNs

P2P and DHTs

Three Hierarchical Assignment Processes

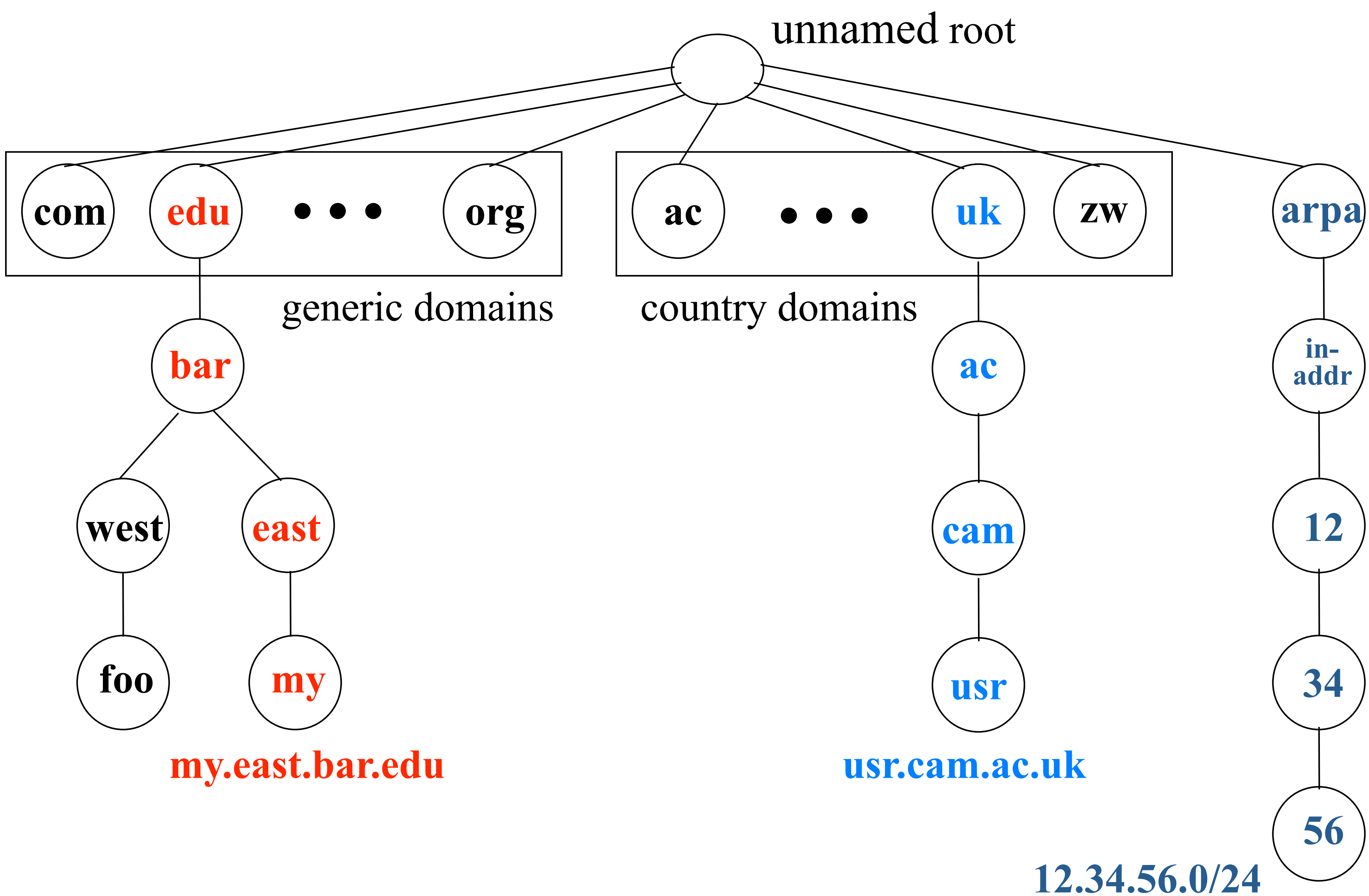
- **Host name:** www.cs.princeton.edu
  - Domain: registrar for each top-level domain (e.g., .edu)
  - Host name: local administrator assigns to each host
- **IP addresses:** 128.112.7.156
  - Prefixes: ICANN, regional Internet registries, and ISPs
  - Hosts: static configuration, or dynamic using DHCP
- **MAC addresses:** 00-15-C5-49-04-A9
  - Blocks: assigned to vendors by the IEEE
  - Adapters: assigned by the vendor from its block

Mapping Between Identifiers

- Domain Name System (DNS)
  - Given a host name, provide the IP address
  - Given an IP address, provide the host name
- Dynamic Host Configuration Protocol (DHCP)
  - Given a MAC address, assign a unique IP address
  - … and tell host other stuff about the Local Area Network
  - To automate the boot-strapping process
- Address Resolution Protocol (ARP)
  - Given an IP address, provide the MAC address
  - To enable communication within the Local Area Network

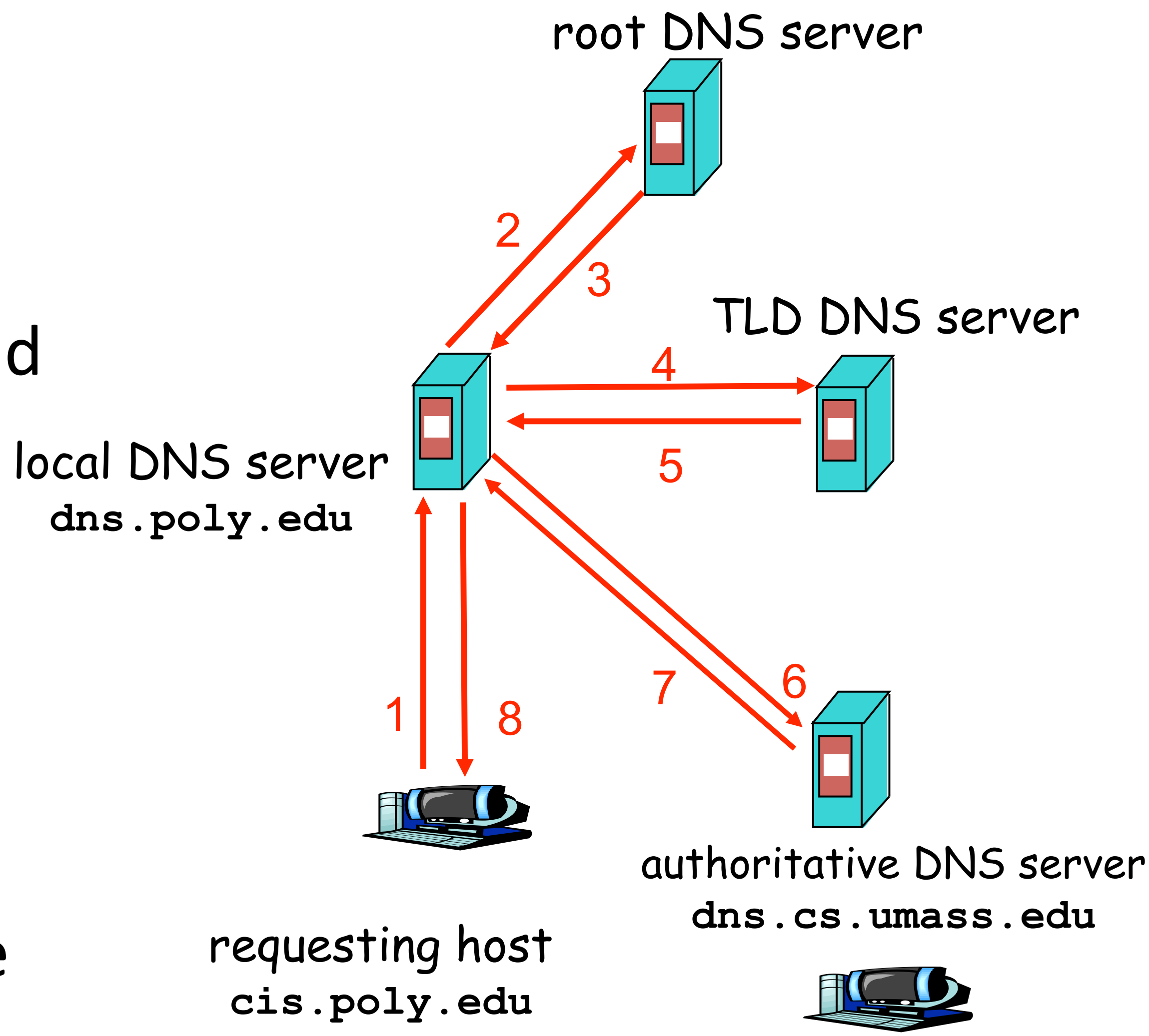
DHCP and ARP use L2 broadcast….DNS is app-layer protocol

DNS: Distributed Hierarchical DB



Recursive vs. Iterative Queries

- Recursive query
  - Ask server to get answer for you
  - E.g., request 1 and response 8
- Iterative query
  - Ask server who to ask next
  - E.g., all other request-response pairs



DNS security

- DNS cache poisoning
  - Ask for www.evil.com
  - Additional section for (www.cnn.com, 1.2.3.4, A)
  - Thanks! I won't bother check what I asked for
- DNS hijacking
  - Let's remember the domain. And the UDP ID.
  - 16 bits: 65K possible IDs
    - What rate to enumerate all in 1 sec? ~32 Mbps
  - Prevention: Also randomize the DNS source port
- Weaknesses led to DNSSec
  - Chain of signatures from root to authoritative DNS server

HTTP Request Example

GET / HTTP/1.1

Accept: */*

Accept-Language: en-us

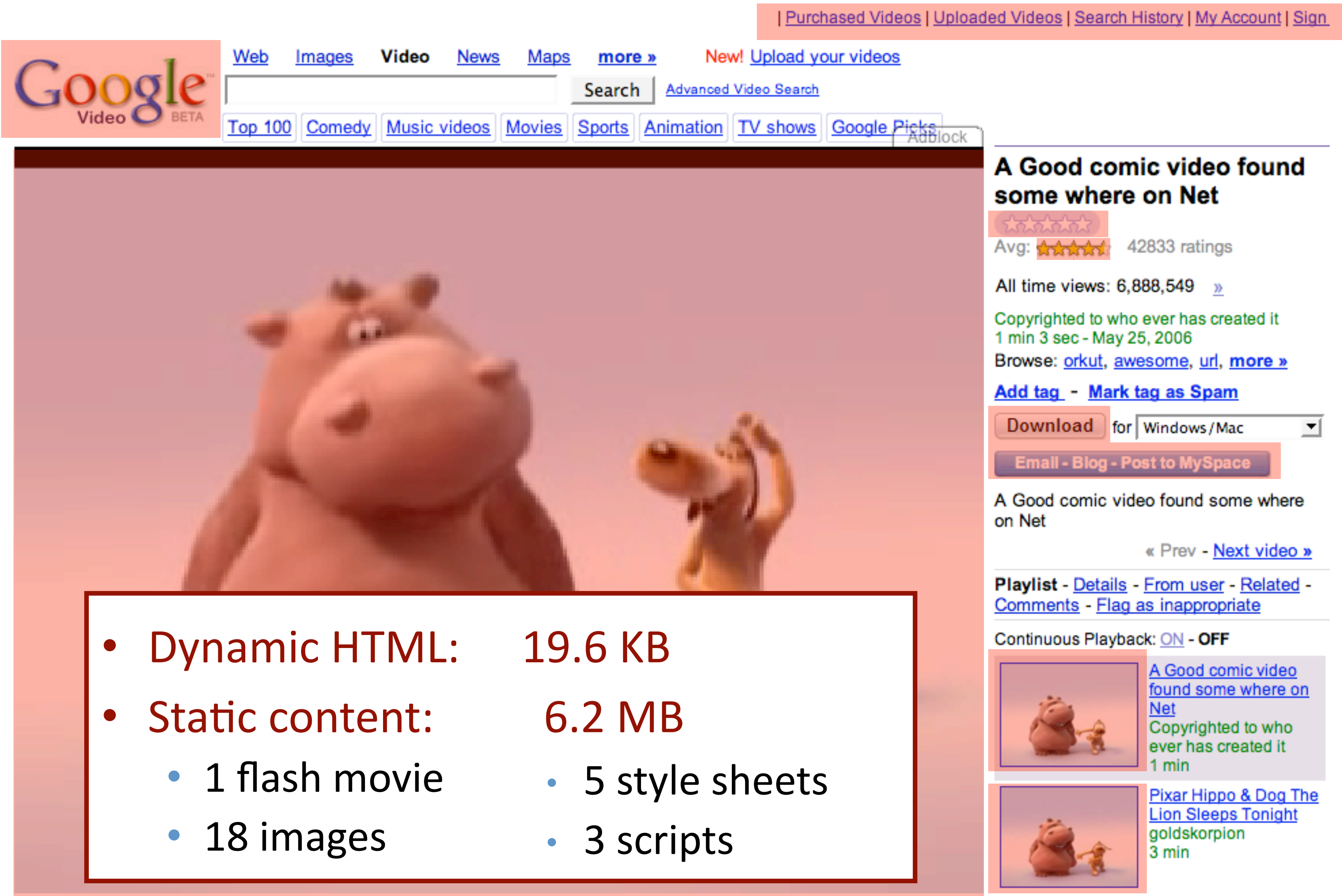
Accept-Encoding: gzip, deflate

User-Agent: Mozilla/4.0 (compatible; MSIE 5.5; Windows NT 5.0)

Host: www.intel-iris.net

Connection: Keep-Alive

One page, lots of objects



- Dynamic HTML: 19.6 KB
- Static content: 6.2 MB
  - 1 flash movie
  - 18 images
  - 5 style sheets
  - 3 scripts

TCP Interaction: Short Transfers

- Multiple connection setups
  - Three-way handshake each time
- Round-trip time estimation
  - Maybe large at the start of a connection (e.g., 3 seconds)
  - Leads to latency in detecting lost packets
- Congestion window
  - Small value at beginning of connection (e.g., 1 MSS)
  - May not reach a high value before transfer is done
- Detecting packet loss
  - Timeout: slow ☹
  - Duplicate ACK
    - Requires many packets in flight
    - Which doesn't happen for very short transfers ☹

Persistent HTTP

Non-persistent HTTP issues:

- Requires 2 RTTs per object
- OS must allocate resources for each TCP connection
- But browsers often open parallel TCP connections to fetch referenced objects

Persistent HTTP:

- Server leaves connection open after sending response
- Subsequent HTTP messages between same client/server are sent over connection

Persistent without pipelining:

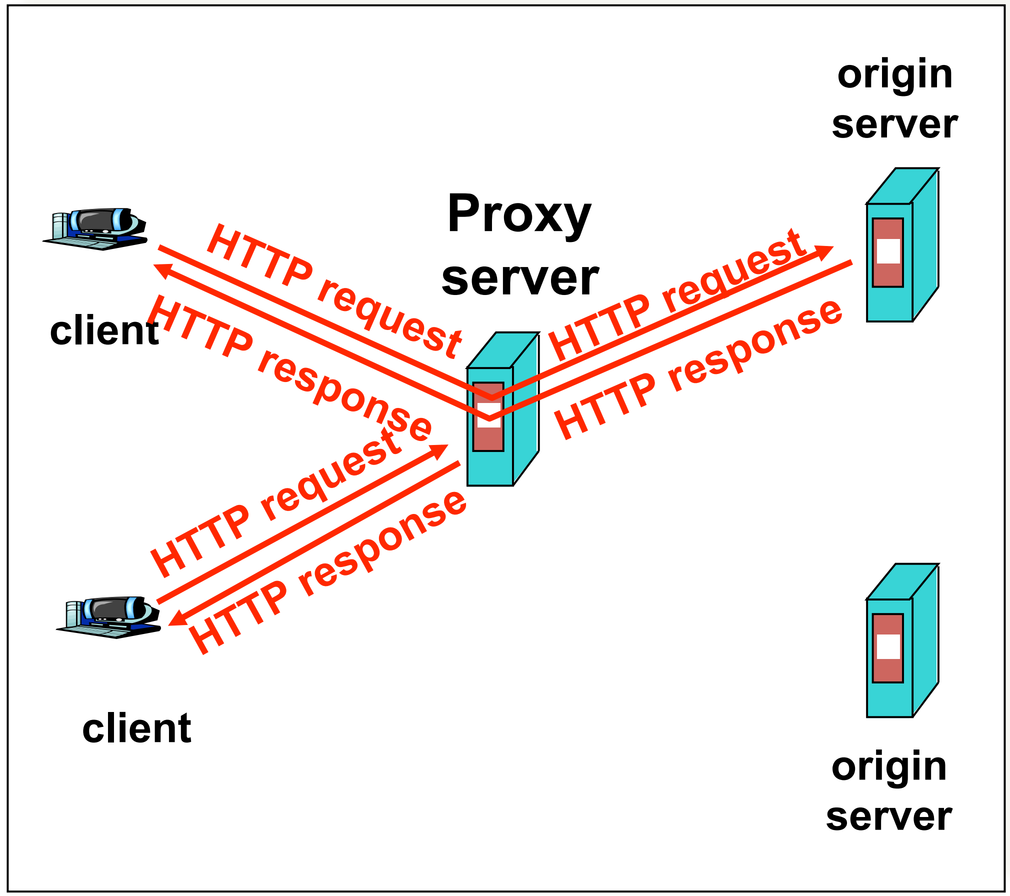
- Client issues new request only when previous response has been received
- One RTT for each object

Persistent with pipelining:

- Default in HTTP/1.1
- Client sends requests as soon as it encounters referenced object
- As little as one RTT for all the referenced objects

Web Proxy Caches

- User configures browser: Web accesses via cache
- Browser sends all HTTP requests to cache
  - Object in cache: cache returns object
  - Else: cache requests object from origin, then returns to client

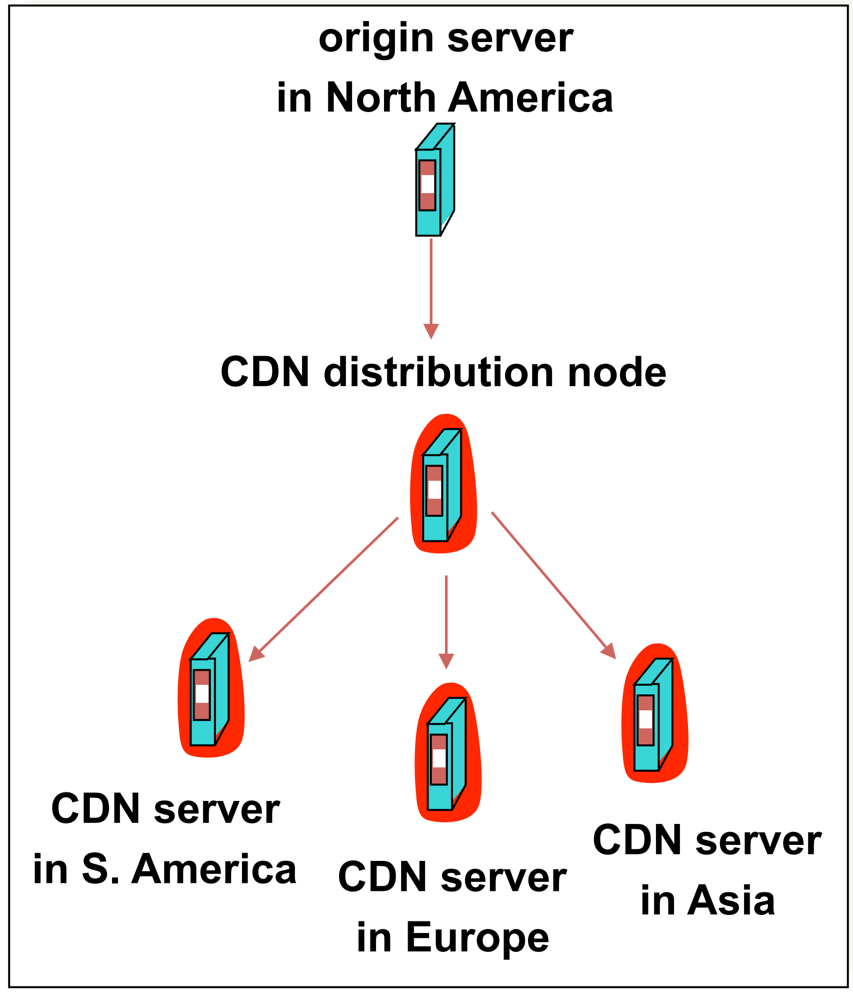


Content Distribution Networks (CDNs)

- Content providers are CDN customers

Content replication

- CDN company installs thousands of servers throughout Internet
  - In large datacenters
  - Or, close to users
- CDN replicates customers' content
- When provider updates content, CDN updates servers

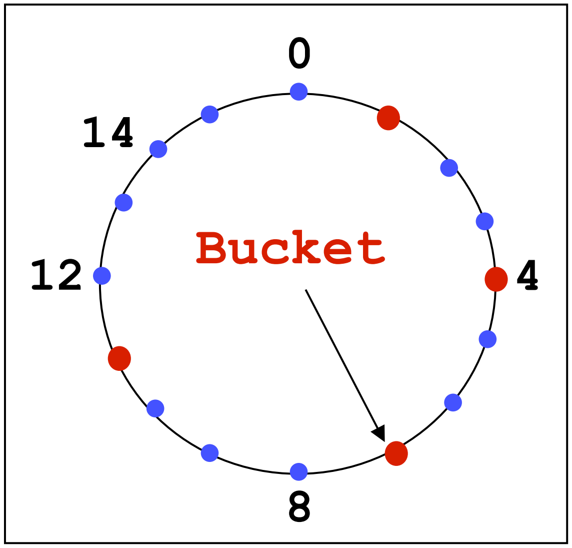


How to perform server selection?

- Routing based (IP anycast)
  - Pros: Transparent to clients, works when browsers cache failed addresses, circumvents many routing issues
  - Cons: Little control, complex, scalability, TCP can't recover, …
- Application based (HTTP redirects)
  - Pros: Application-level, fine-grained control
  - Cons: Additional load and RTTs, hard to cache
- Naming based (DNS selection)
  - Pros: Well-suitable for caching, reduce RTTs
  - Cons: Request by resolver not client, request for domain not URL, hidden load factor of resolver's population
    - Much of this data can be estimated "over time"

Consistent Hashing

- Construction
  - Assign each of C hash buckets to random points on mod 2^n circle; hash key size = n
  - Map object to random position on circle
  - Hash of object = closest clockwise bucket

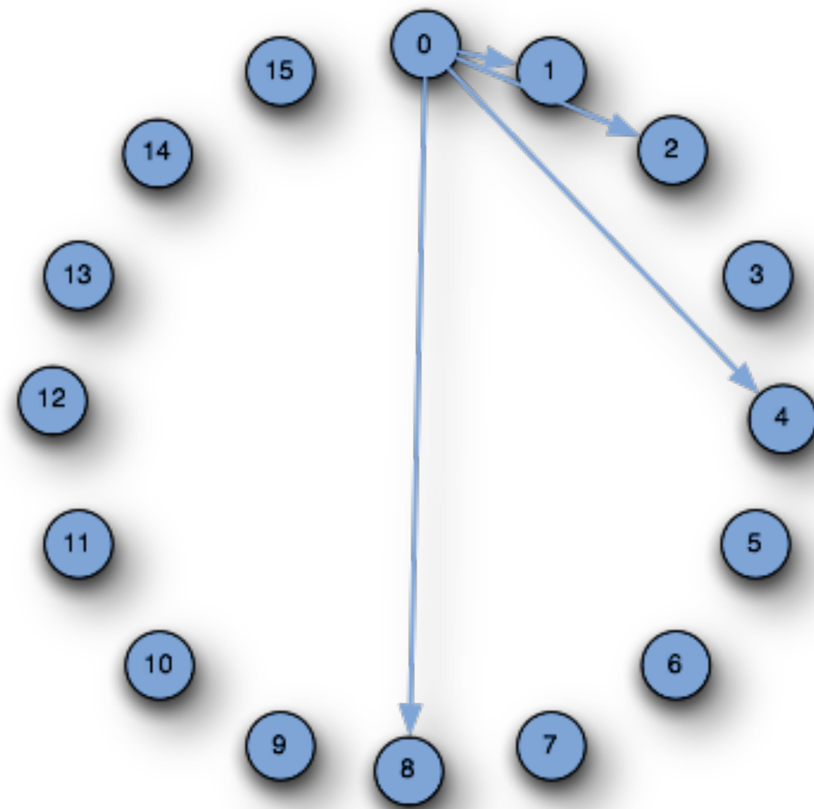


- Desired features
  - Balanced: No bucket responsible for large number of objects
  - Smoothness: Addition of bucket does not cause movement among existing buckets
  - Spread and load: Small set of buckets that lie near object

- Used layer in P2P Distributed Hash Tables (DHTs)

Extended consistent hashing to large-scale systems

- Chord: each node has small view of network
  - k immediate successors
  - log n long-distance "fingers"



- Performing lookup(k)
  - Greedily route to closest nodeid
  - Each step get ½ closer
  - Takes log n hops

Topics

- Link layer:
  - Ethernet and CSMA/CD
  - Wireless protocols and CSMA/CA
  - Spanning tree, switching and bridging
  - Translating addrs: DHCP and ARP
- Network layer:
  - IPv4, addressing, and forwarding
  - IP routing
    - Link-state and distance vector
    - BGP: path vector, policies
  - IP multicast and anycast
  - Middleboxes: NATs, firewalls
  - Tunneling: MPLS, IPSec
  - Addt. Considerations: mobility, DTNs
- Transport layer:
  - Socket interface
  - UDP
  - TCP
    - Reliability
    - Congestion Control
  - Reliable multicast
- Application layer:
  - Translating names: DNS
  - HTTP and CDNs
  - Overlay networks
  - Peer-to-peer and DHTs
  - Email