EECS 489
Computer Networks

Winter 2024

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Material with thanks to Aditya Akella, Sugih Jamin, Philip Levis, Sylvia Ratnasamy, Peter Steenkiste, and many other colleagues.

Logistics

- Open book/text/notes, but OFFLINE
  - Except for taking the exam over the Internet
- You’re NOT allowed to write/run any programs
- You’re NOT allowed to collaborate with anyone
- You’re NOT allowed to use any AI

General guidelines (1)

- Test only assumes material covered in lecture, discussion sections, quizzes, and assignments
    - Text: only to clarify details and context for the above
- The test doesn't require you to do complicated calculations
    - Use this as a hint to determine if you're on right track
- You don't need to memorize anything
- You do need to understand how things work

General guidelines (2)

- Be prepared to:
  - Weigh design options outside of the context we studied them in
  - Contemplate new designs we haven't covered in detail but can be put together
    - e.g., I introduce a new IP address format; how does this affect.."
  - Reason from what you know about the pros/cons of solutions we did study

General guidelines (3)

- Exam format
  - Q1: True-False questions
  - Q2: MCQ questions
  - Q3-QN networking use cases
    - Questions not ordered in terms of complexity

General guidelines (4)

- 60-minute midterm exam on canvas
  - **Mar 6**
  - **Available from 9:30AM**
  - **Due at 1PM**

This review

- Walk through what you're expected to know at this point: key topics, important aspects of each
- Not covered in review does NOT imply you don't need to know it
  - But if it's covered today, you should know it
- Summarize, not explain
  - Stop me when you want to discuss something further!

Topics

- Basics (lectures 1–2)
- Application layer (lectures 3–5)
  - HTTP, DNS, CDN, Video Streaming, and Cloud
- Transport layer (lectures 6–9)
  - UDP vs. TCP
  - TCP details: reliability and flow control
  - TCP congestion control: general concepts only
- Network layer (lecture 10–11)
  - Overview
  - Data plane

Basic concepts

- You should know:
  - Packet vs. circuit switching
  - Statistical multiplexing
  - Link characteristics
  - Packet delays

Switched networks

- End-systems and networks connected by switches instead of directly connecting them
- Allows us to scale
  - For example, directly connecting N nodes to each other would require N^2 links!

Two approaches to sharing

- Packet switching
  - Network resources consumed on demand per-packet
  - Admission control: per packet
- Circuit switching
  - Network resources reserved a priori at “connection” initiation
  - Admission control: per connection

Statistical multiplexing

- Allowing more demands than the network can handle
  - Hoping that not all demands are required at the same time
  - Good for bursty traffic (average << peak demand)
  - Packet switching exploits statistical multiplexing better than circuit switching

Delay

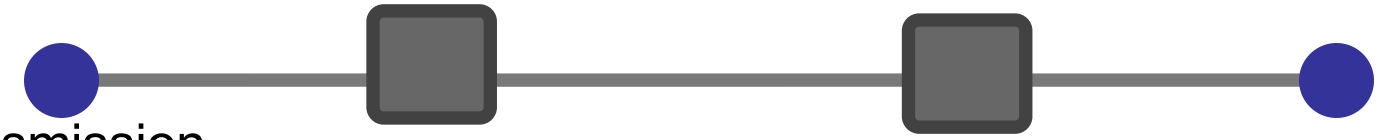
- Consists of four components
  - Transmission delay
  - Propagation delay

  due to link properties

  - Queuing delay
  - Processing delay

  due to traffic mix and switch internals

End-to-end delay



transmission

propagation

queueing

processing

transmission

propagation

queueing

processing

transmission

propagation

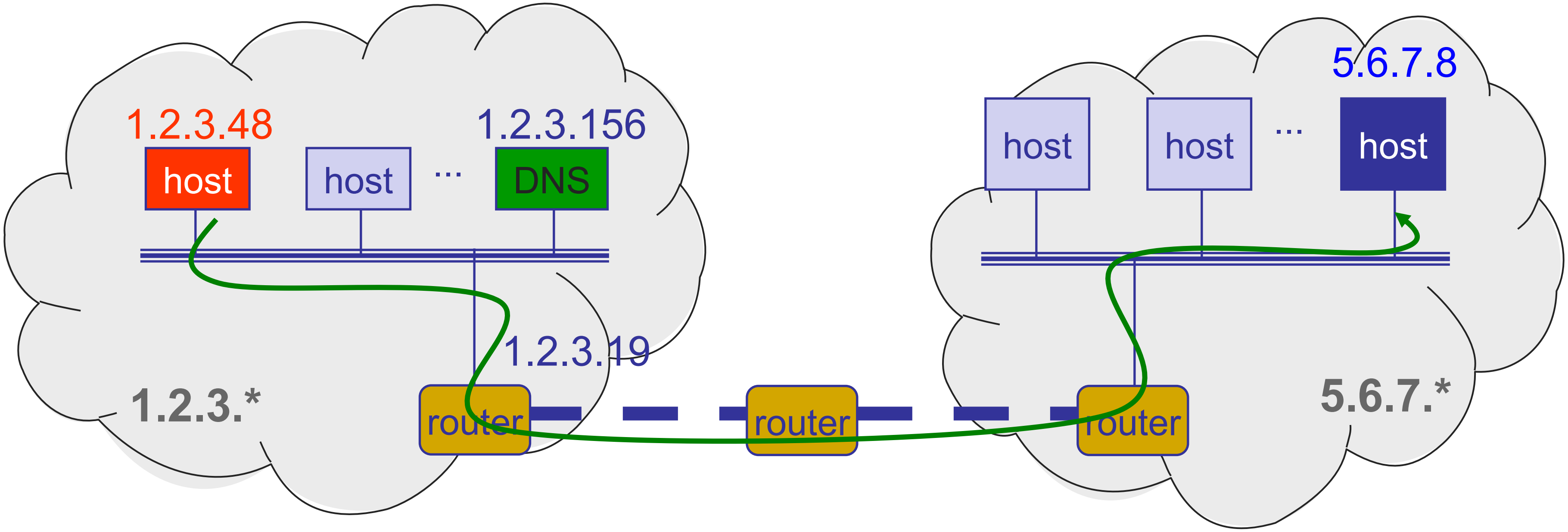
We only consider store-and-forward in this class

What we want

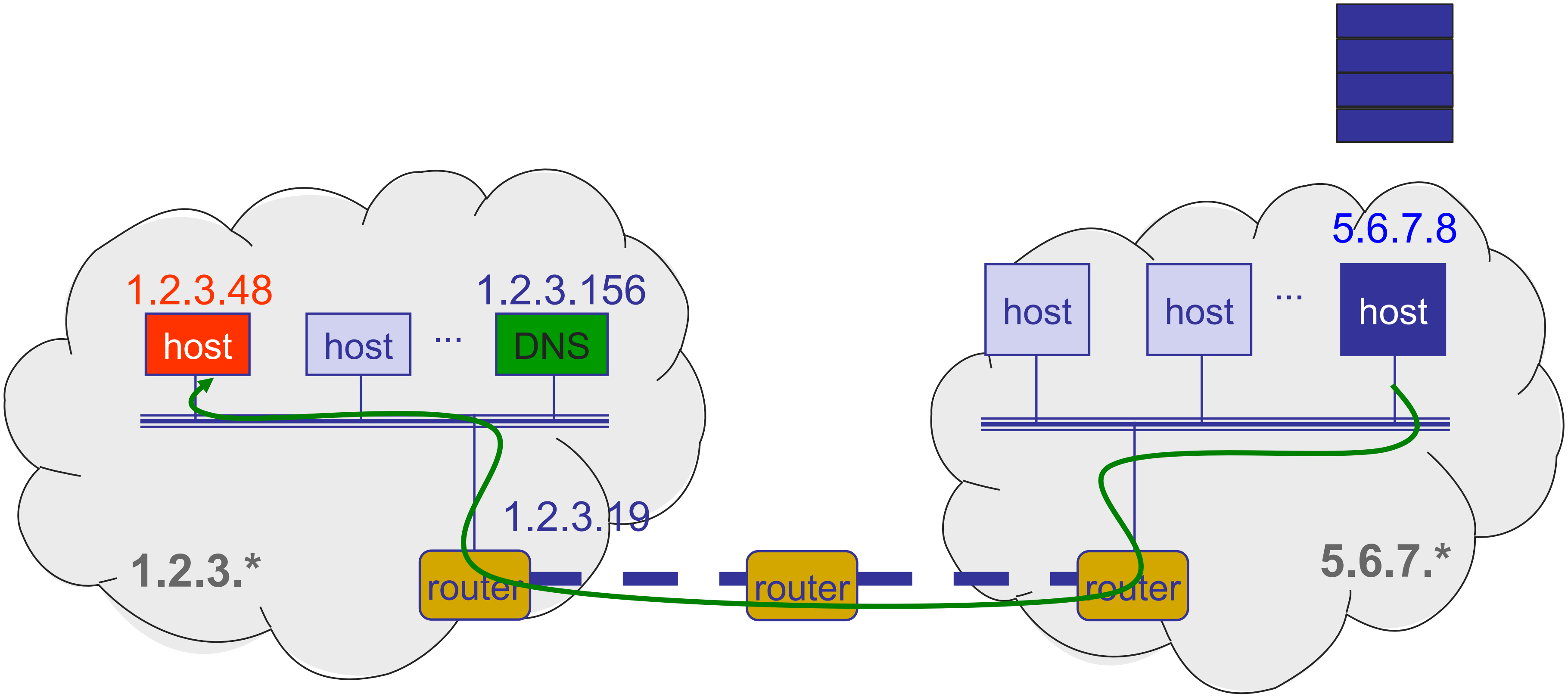
http://123.xyz

123.xyz server

(Some of) What happens...



(More of) What happens



What we get

http://123.xyz

Hello

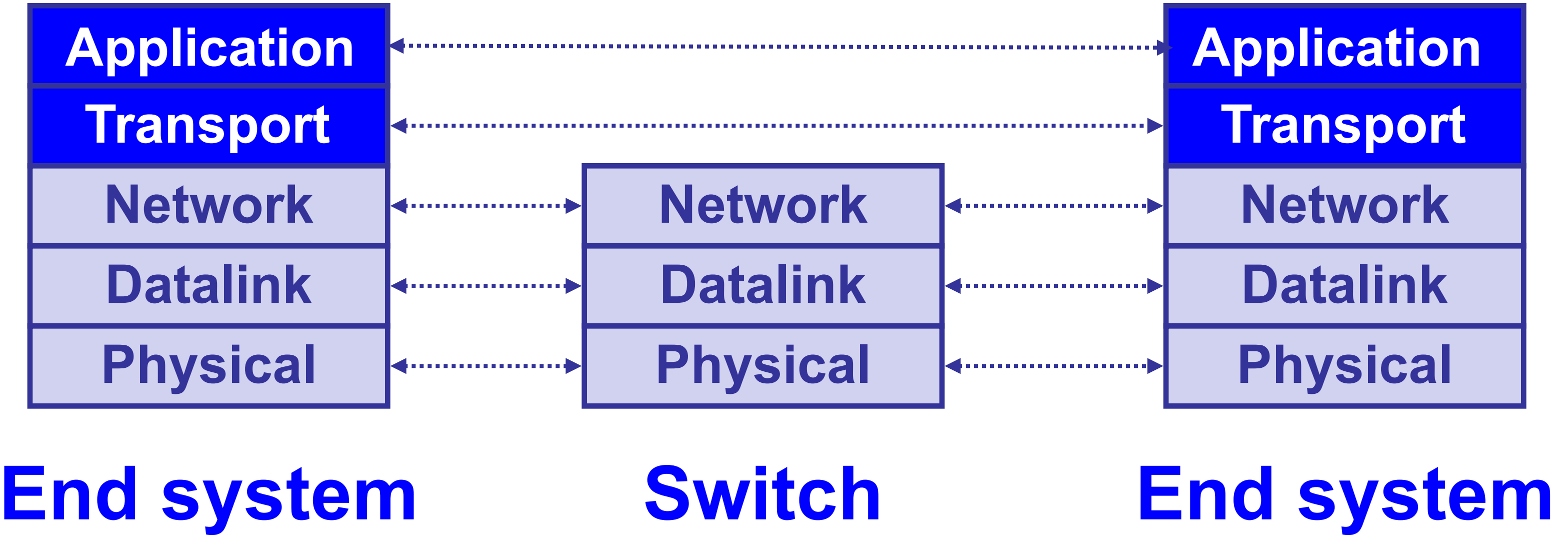
123.xyz server

Layers

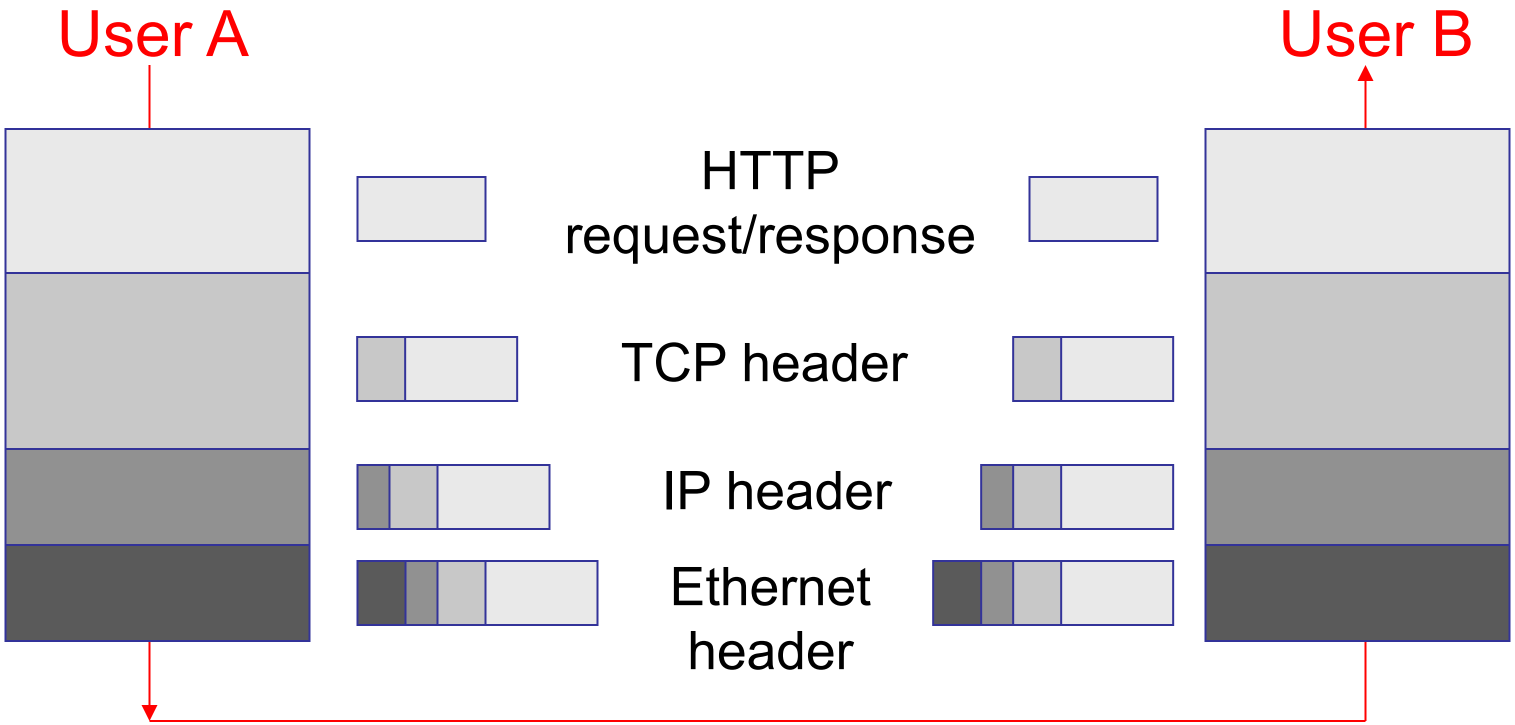
- Layer: a part of a system with well-defined interfaces to other parts
- One layer interacts only with layer above and layer below
- Two layers interact only through the interface between them

Layers in practice

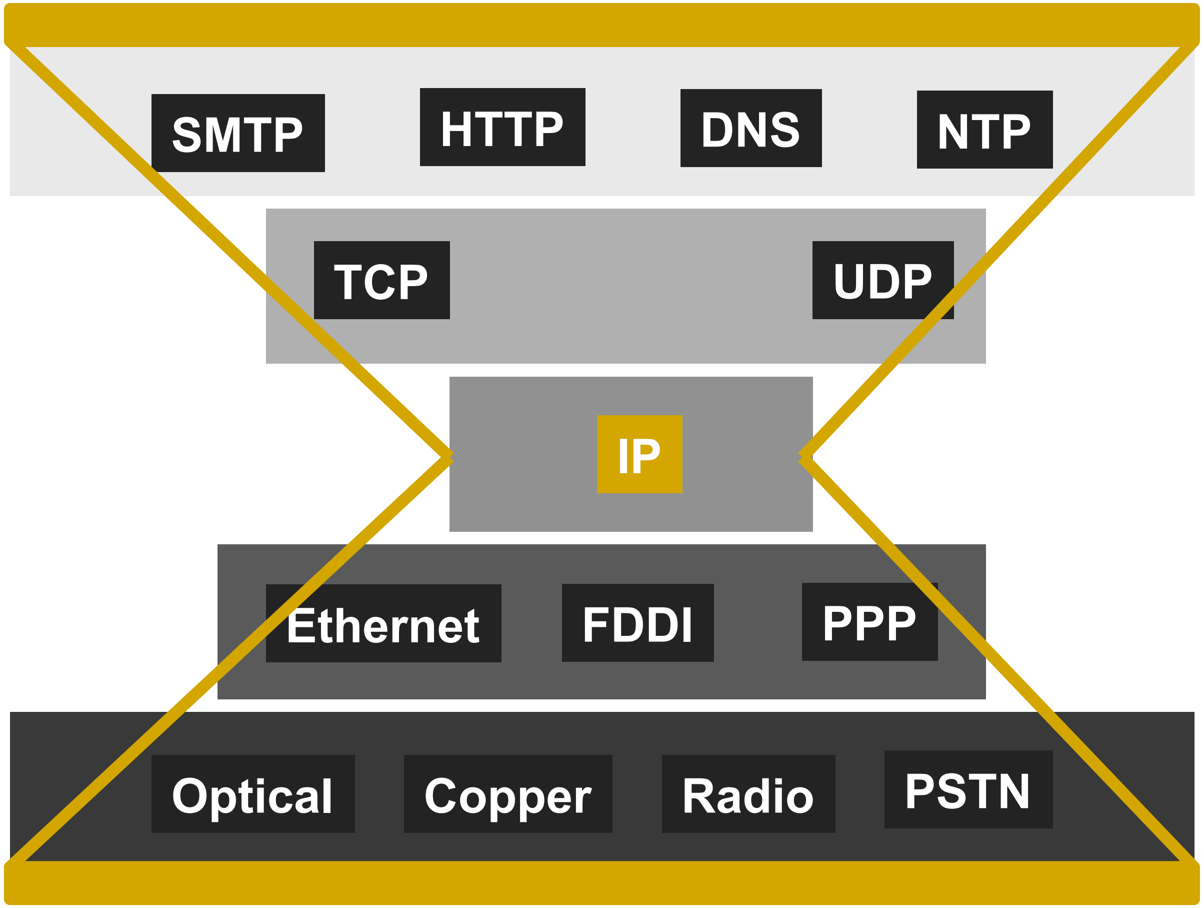
- Lower three layers implemented everywhere
- Top two layers implemented only at hosts



Layer encapsulation: Protocol headers



IP is the narrow waist of the layering hourglass



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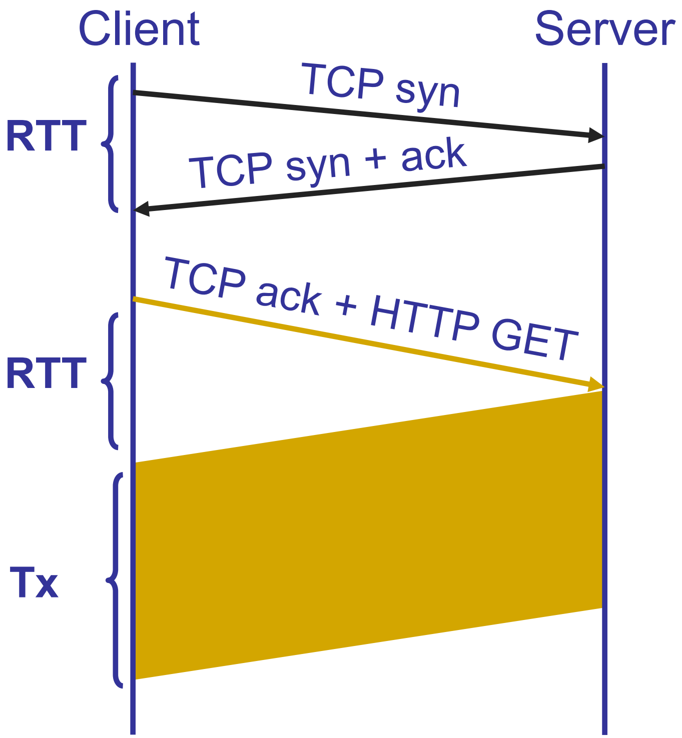
Hyper Text Transfer Protocol (HTTP)

- Client-server architecture
  - Server is “always on” and “well known”
  - Clients initiate contact to server
- Synchronous request/reply protocol
  - Runs over TCP, Port 80
- Stateless
- ASCII format
  - Before HTTP/2

Object request response time

- RTT (round-trip time)
  - Time for a small packet to travel from client to server and back
- Response time
  - 1 RTT for TCP setup
  - 1 RTT for HTTP request and first few bytes
  - Transmission time
  - Total = 2RTT + Transmission Time



Improving HTTP performance

- Optimizing connections using three "P"s
  - Persistent connections
  - Parallel/concurrent connections
  - Pipelined transfers over the same connection
- Caching
  - Forward proxy: close to clients
  - Reverse proxy: close to servers
- Replication

Scorecard: Getting n small objects

- Time dominated by latency

- One-at-a-time: ~2n RTT
- m concurrent: ~2[n/m] RTT
- Persistent: ~ (n+1) RTT
- Pipelined: ~2 RTT
- Pipelined and Persistent: ~2 RTT first time; RTT later for another n from the same site

Scorecard: Getting n large objects each of size F

- Time dominated by TCP throughput B_C (<= B_L), where bottleneck link bandwidth is B_L
  - Assuming all TCP connections go through the same bottleneck link
- One-at-a-time: ~ nF/B_C
- m concurrent: ~ $nF/(mB'_C)$
  - Assuming each TCP connection gets the same throughput (B'_C), where $mB'_C <= B_L$
- Pipelined and/or persistent: ~ nF/B_C
  - The only thing that helps is higher throughput

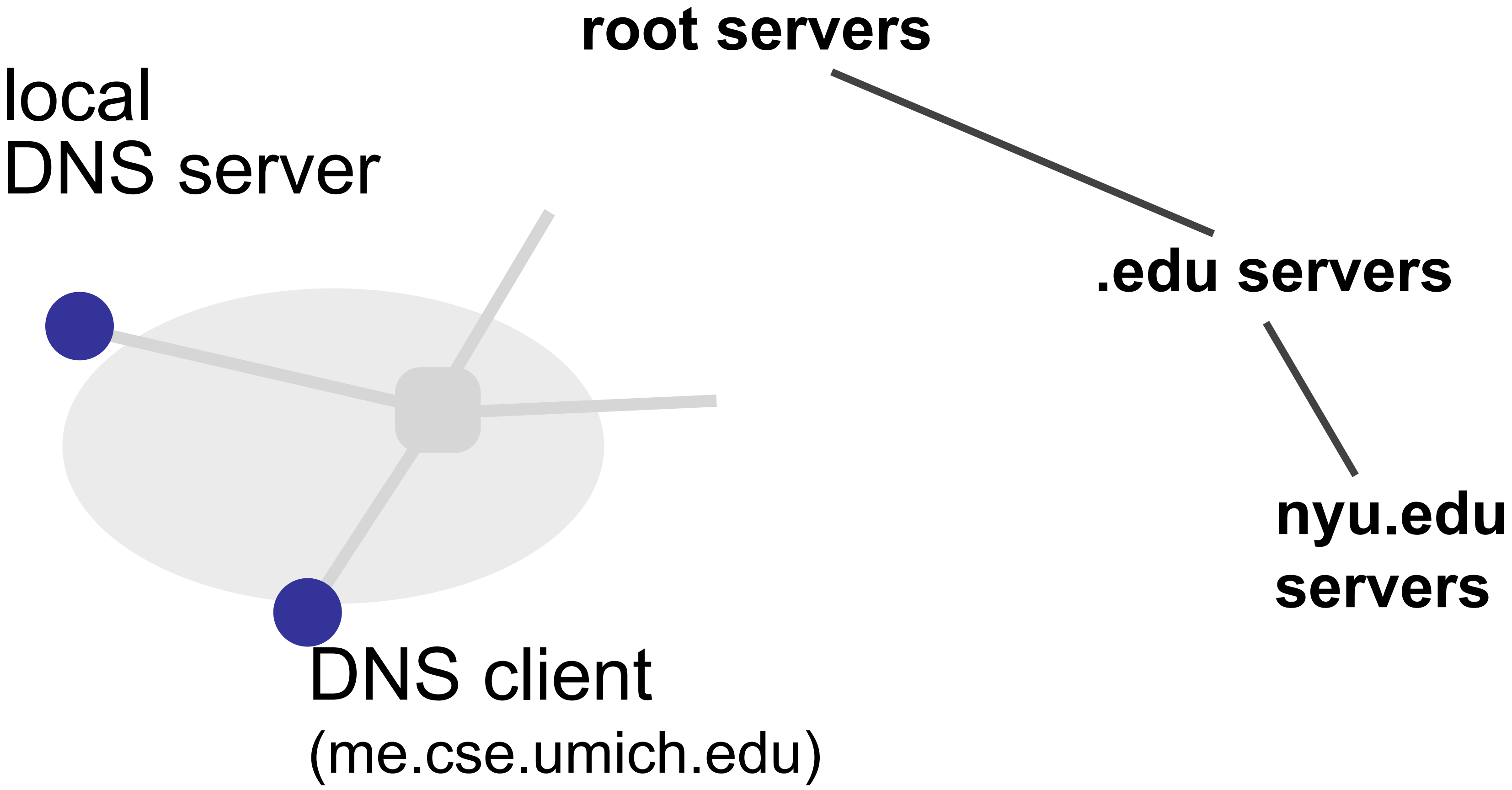
Content Distribution Networks (CDN)

- Caching and replication as a service
- Combination of caching and replication
  - Pull: Direct result of clients' requests (caching)
  - Push: Expectation of high access rate (replication)

Hierarchies in the DNS

- Three intertwined hierarchies
  - Hierarchical namespace
    - As opposed to flat namespace
  - Hierarchically administered
    - As opposed to centralized
  - (Distributed) hierarchy of servers
    - As opposed to centralized storage

Name resolution



root servers

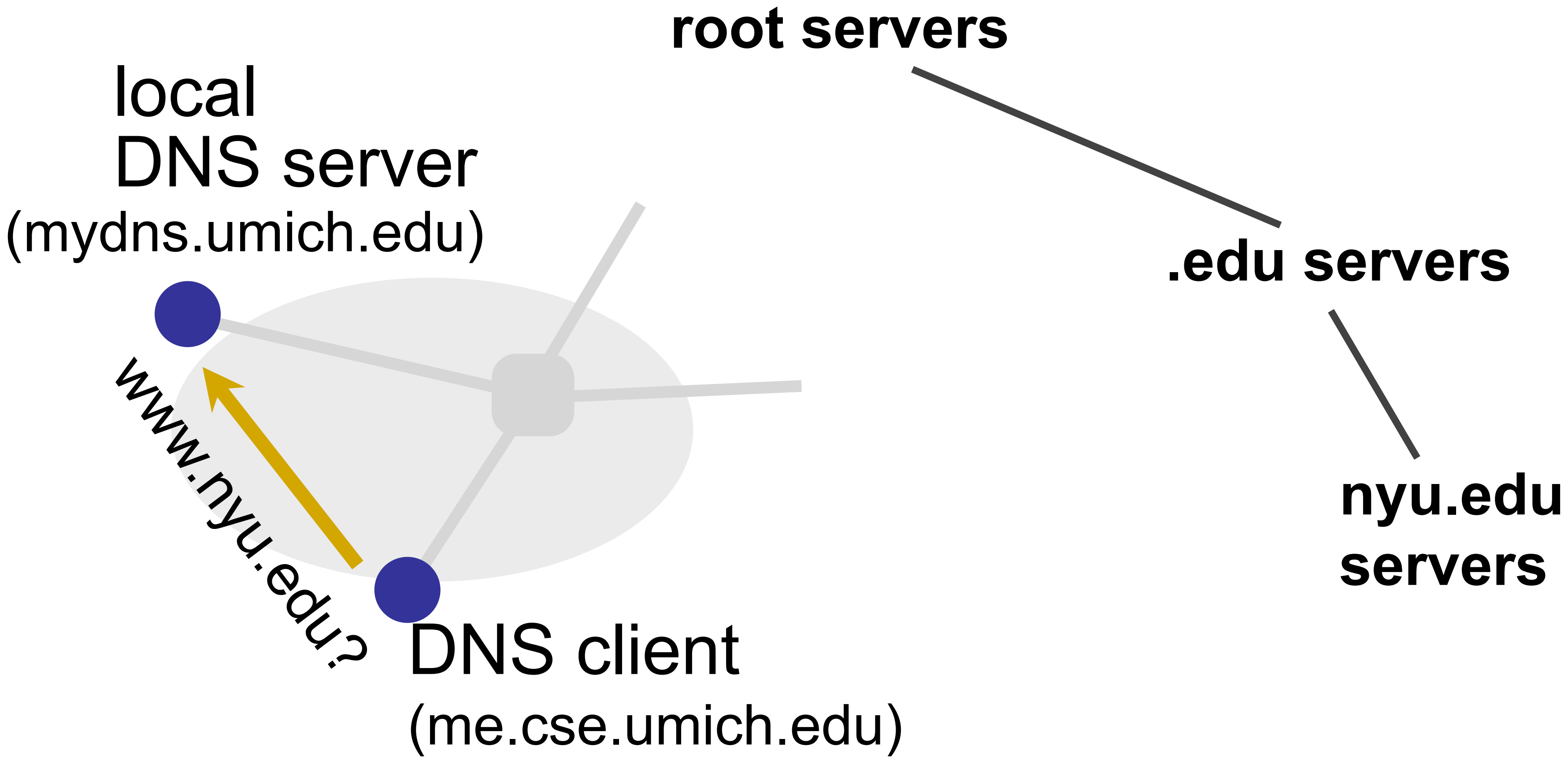
local
DNS server

.edu servers

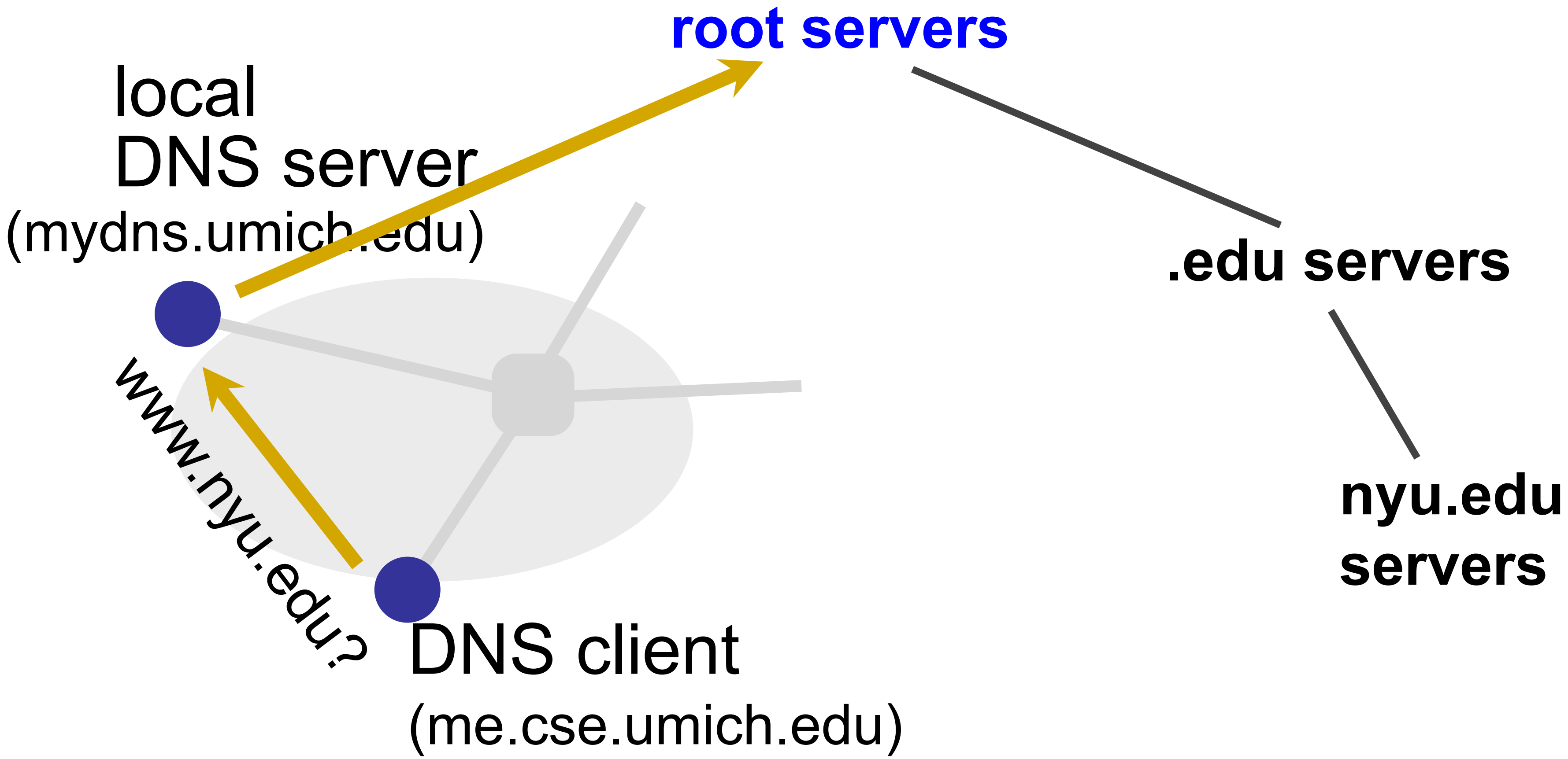
nyu.edu
servers

DNS client
(me.cse.umich.edu)

Name resolution



Name resolution



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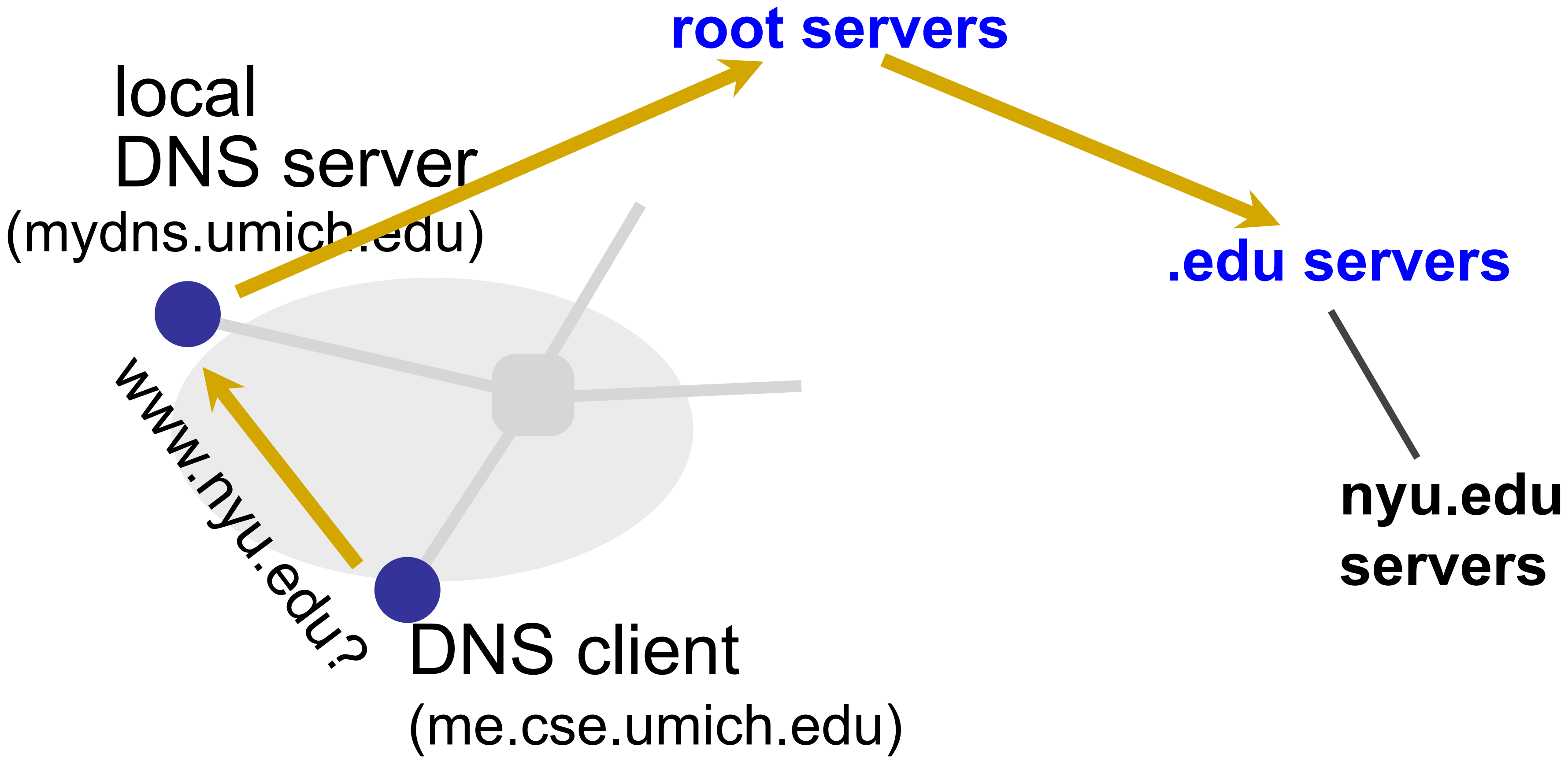
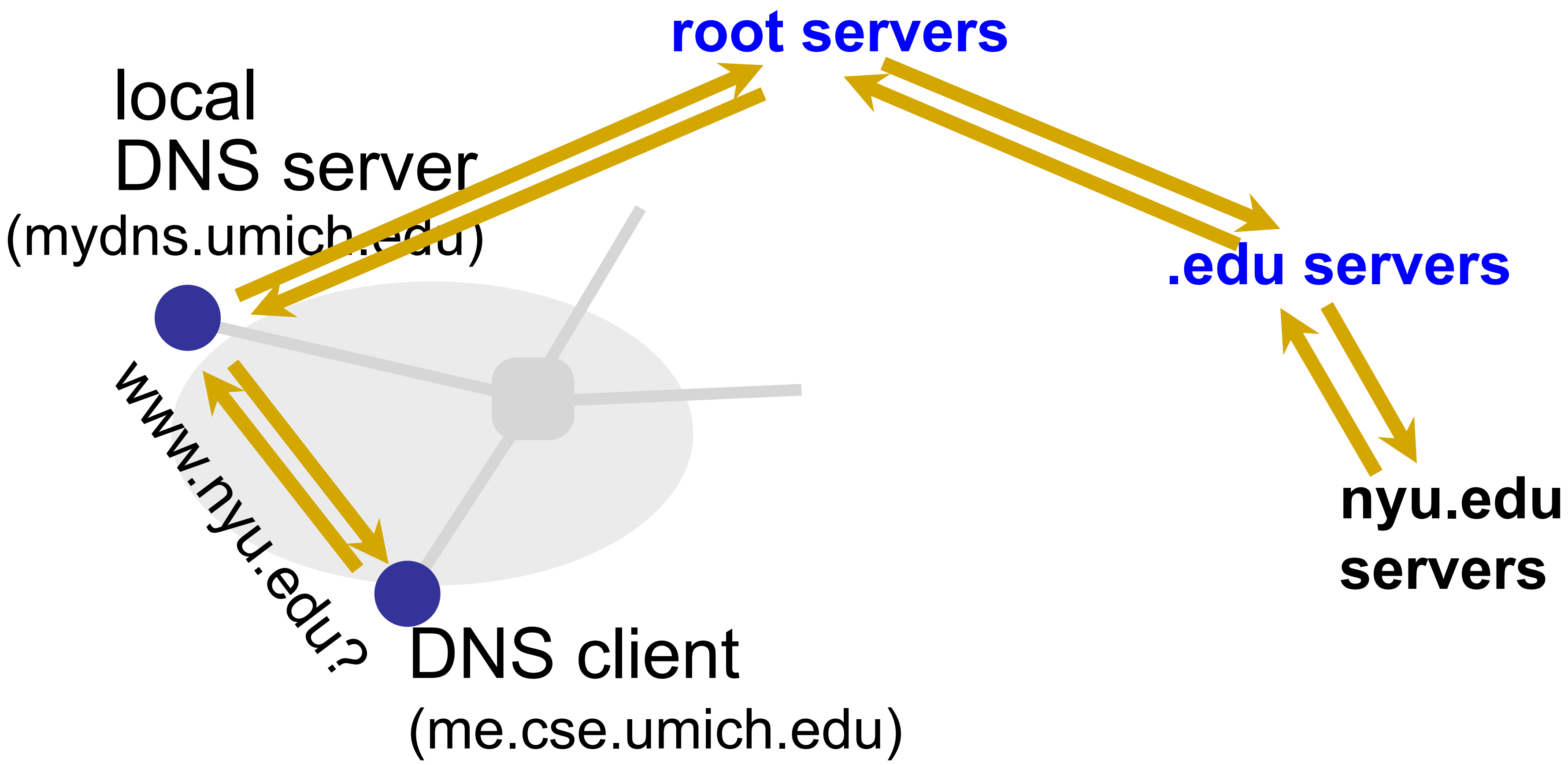
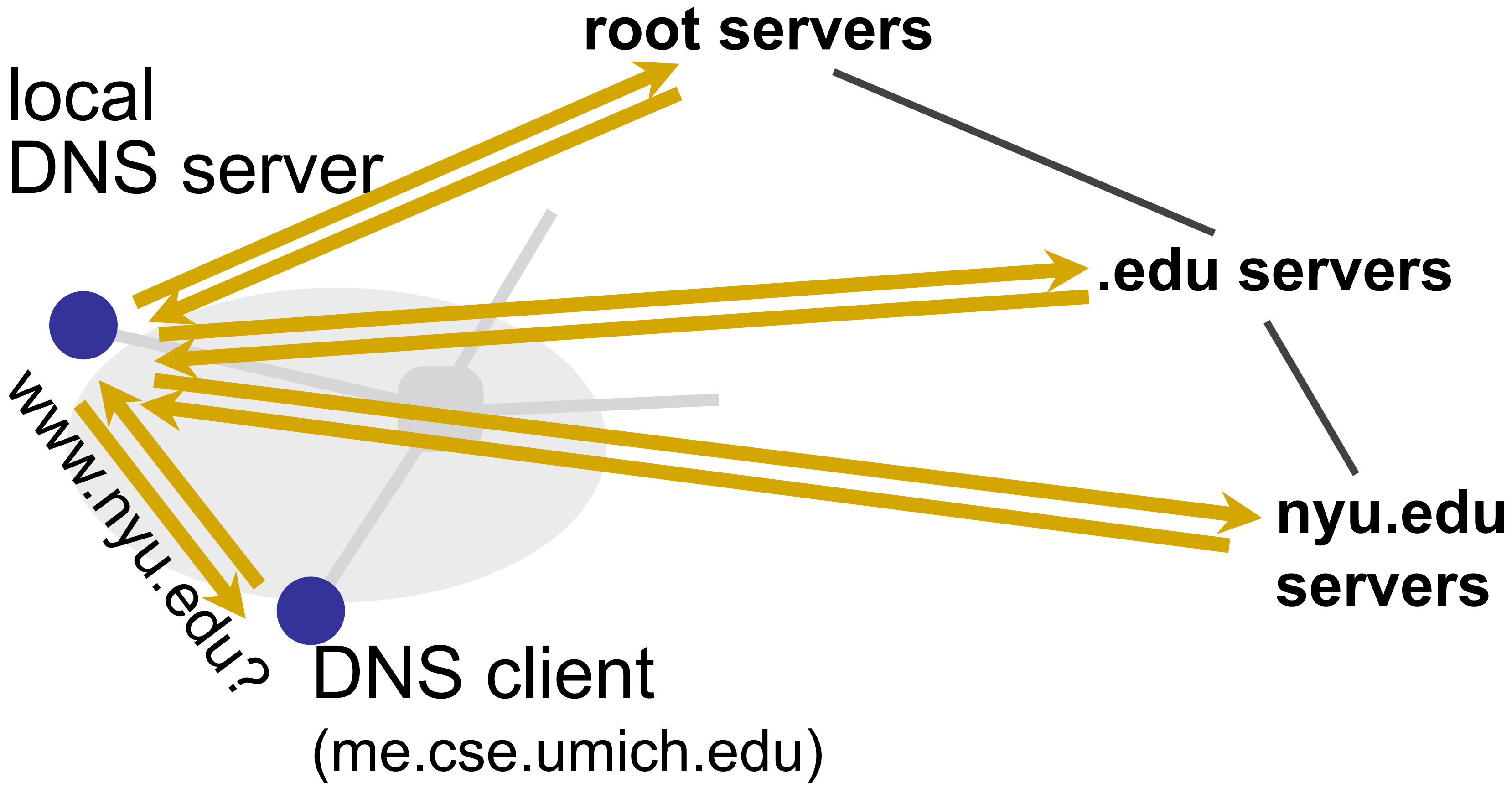


Name resolution: Recursive



Name resolution: Iterative



DNS caching

- Performing all these queries takes time
  - Up to 1-second latency before starting download
- Caching can greatly reduce overhead
  - The top-level servers very rarely change
  - Popular sites (e.g., www.google.com) visited often
  - Local DNS server often has the information cached
- How DNS caching works
  - DNS servers cache responses to queries
  - Responses include a "time to live" (TTL) field
  - Server deletes cached entry after TTL expires

HTTP streaming

- Video is stored at an HTTP server with a URL
- Clients send a GET request for the URL
- Server sends the video file as a stream
- Client first buffers for a while to minimize interruptions later
- Once the buffer reaches a threshold
  - The video plays in the foreground
  - More frames are downloaded in the background

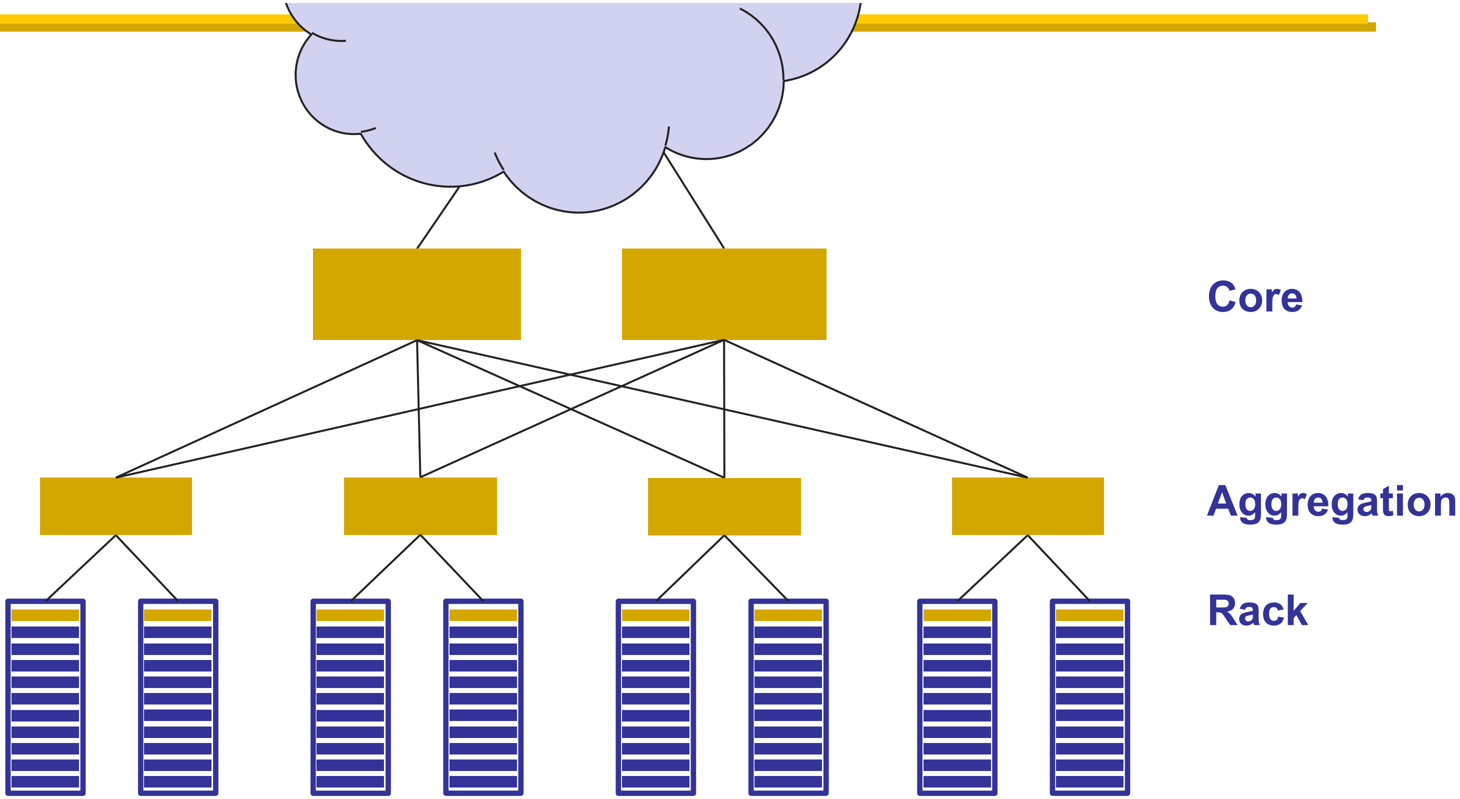
DASH : Dynamic Adaptive Streaming over HTTP

- Keep multiple resolutions of the same video
  - Stored in a manifest file in the HTTP server
- Client asks for the manifest file first to learn about the options
- Asks for chunks at a time and measures available bandwidth while they are downloaded
  - Low bandwidth ⇒ switch to lower bitrate
  - High bandwidth ⇒ switch to higher bitrate

Applications

- Common theme: parallelism
  - Applications decomposed into tasks
  - Running in parallel on different machines
- Two common paradigms
  - Partition-Aggregate
  - Map-Reduce

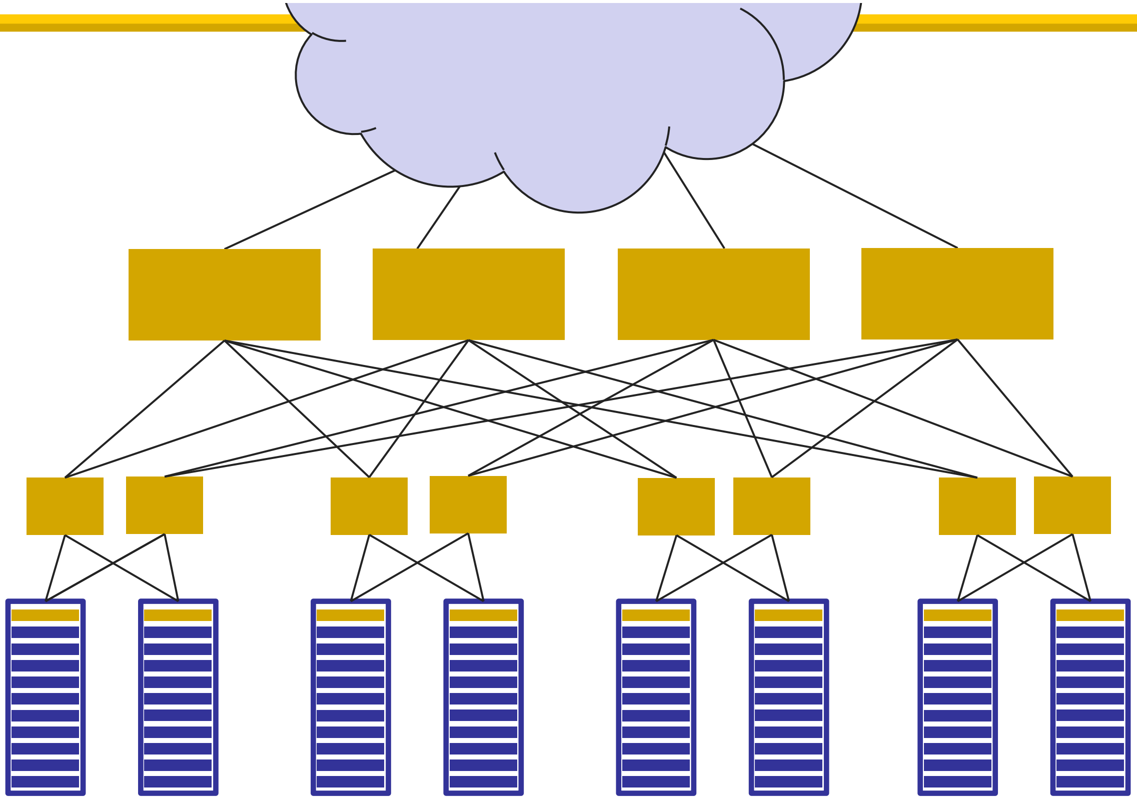
Traditional datacenter networks



Challenges

- Not enough bandwidth
  - Oversubscription: Less bandwidth in the ToR-Agg links than all the servers' bandwidth in the rack
  - Oversubscription ratio: Ratio between bandwidth underneath and bandwidth above
- Not enough paths between server pairs
  - Load balancing issues
  - Failure recovery issues

Modern datacenter networks: More bandwidth, more paths



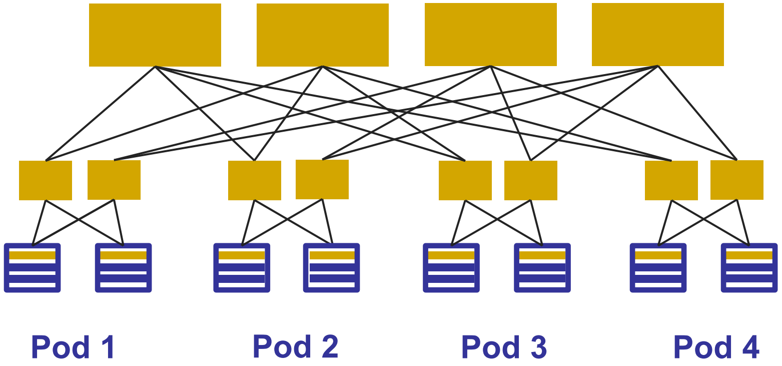
Core

Aggregation

Rack

Clos topology

- Multi-stage network
- k pods, where each pod has two layers of k/2 switches
  - k/2 ports up and k/2 down
- All links have the same b/w
- At most $k^3/4$ machines



- Example
  - k = 4
  - 16 machines
- For k=48, 27648 machines

5-MINUTE BREAK!

Announcements

- 60-minute midterm exam on canvas
    - **Mar 6**
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- Please fill up midterm teaching evaluation

Topics

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Role of the transport layer

- (1) Communication between application processes
  - Mux and demux from/to application processes
  - Implemented using ports
- (2) Provide common end-to-end services for app layer
  - Reliable, in-order data delivery
  - Well-paced data delivery

UDP vs. TCP

- Both UDP and TCP perform mux/demux via ports

	UDP	TCP
Data abstraction	Packets (datagrams)	Stream of bytes of arbitrary length
Service	Best-effort (same as IP)	•Reliability •In-order delivery •Congestion control •Flow control

Reliable transport: General concepts

- Checksums (for error detection)
- Timers (for loss detection)
- Acknowledgments (feedback from receiver)
  - Cumulative: “received everything up to X”
  - Selective: “received X”
- Sequence no (detect duplicates, accounting)
- Sliding windows (for efficiency)

You should know:

- what these concepts are
- why they exist
- how TCP uses them

Designing a reliable transport protocol

- Stop and wait is correct but inefficient
  - Works packet by packet (of size DATA)
  - Throughput is (DATA/ RTT)
- Sliding window: use pipelining to increase throughput
  - n packets at a time results in higher throughput
  - MIN(n*DATA/RTT, Link Bandwidth)

The TCP abstraction

- TCP delivers a reliable, in-order, byte stream
- Reliable: TCP resends lost packets (recursively)
  - Until it gives up and shuts down connection
- In-order: TCP only hands consecutive chunks of data to application
- Byte stream: TCP assumes there is an incoming stream of data, and attempts to deliver it to app

Things to know about TCP

- How TCP achieves reliability
- RTT estimation
- Connection establishment/teardown
- Flow Control
- Congestion Control (concepts only)

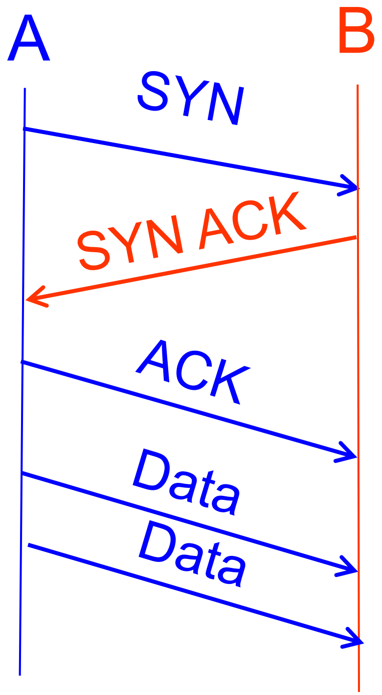
- For each, know how the functionality is implemented and why it is needed

Reliability

- Having TCP take care of it simplifies application development
- How
  - Checksums and timers (for error and loss detection)
  - Fast retransmit (to detect faster-than-timeout loss)
  - Cumulative ACKs (receiver feedback: what’s lost?)
  - Sliding windows (for efficiency)
  - Buffers at sender (hold packets until ACKs arrive)
  - Buffers at receiver (to reorder packets before delivery to application)

Establishing/terminating a TCP connection

- Three-way handshake to establish connection
  - Host A sends a SYN (open; “synchronize sequence numbers”) to host B
  - Host B returns a SYN acknowledgment (SYN ACK)
  - Host A sends an ACK to acknowledge the SYN ACK
- Three-way handshake to terminate (normal operation)



Flow control

- Why?
  - TCP at the receiver must buffer a packet until all packets before it (in byte-order) have arrived and the receiving application has consumed available bytes
  - Hence, receiver advances its window when the receiving application consumes data
  - Sender advances its window when new data ACK'd
  - Risk of sender overrunning the receiver's buffers
- How?
  - "Advertised Window" field in TCP header

Congestion control

- Why?
  - Because the network itself can be the bottleneck
  - Should make efficient use of available network capacity
    - »While sharing available capacity fairly with other flows
    - »And adapting to changes in available capacity
- How?
  - Dynamically adapts the size of the sending window

Put together

- Flow Control
  - Restrict window to RWND to make sure that the receiver isn’t overwhelmed
- Congestion Control
  - Restrict window to CWND to make sure that the network isn’t overwhelmed
- Together
  - Restrict window to min{RWND, CWND} to make sure that neither the receiver nor the network are overwhelmed

CC implementation

- States at sender
  - CWND (initialized to a small constant)
  - ssthresh (initialized to a large constant)
  - dupACKcount and timer
- Events
  - ACK (new data)
  - dupACK (duplicate ACK for old data)
  - Timeout

Event: ACK (new data)

- If CWND < ssthresh
  - CWND += 1

- *CWND packets per RTT*
- *Hence, after one RTT with no drops:*

  CWND = 2xCWND

Event: ACK (new data)

- If CWND < ssthresh
  - CWND += 1

***Slow start* phase**

- Else
  - CWND = CWND + 1/CWND

***Congestion avoidance* phase**

- *CWND packets per RTT*
- *Hence, after one RTT with no drops:*
  CWND = CWND + 1

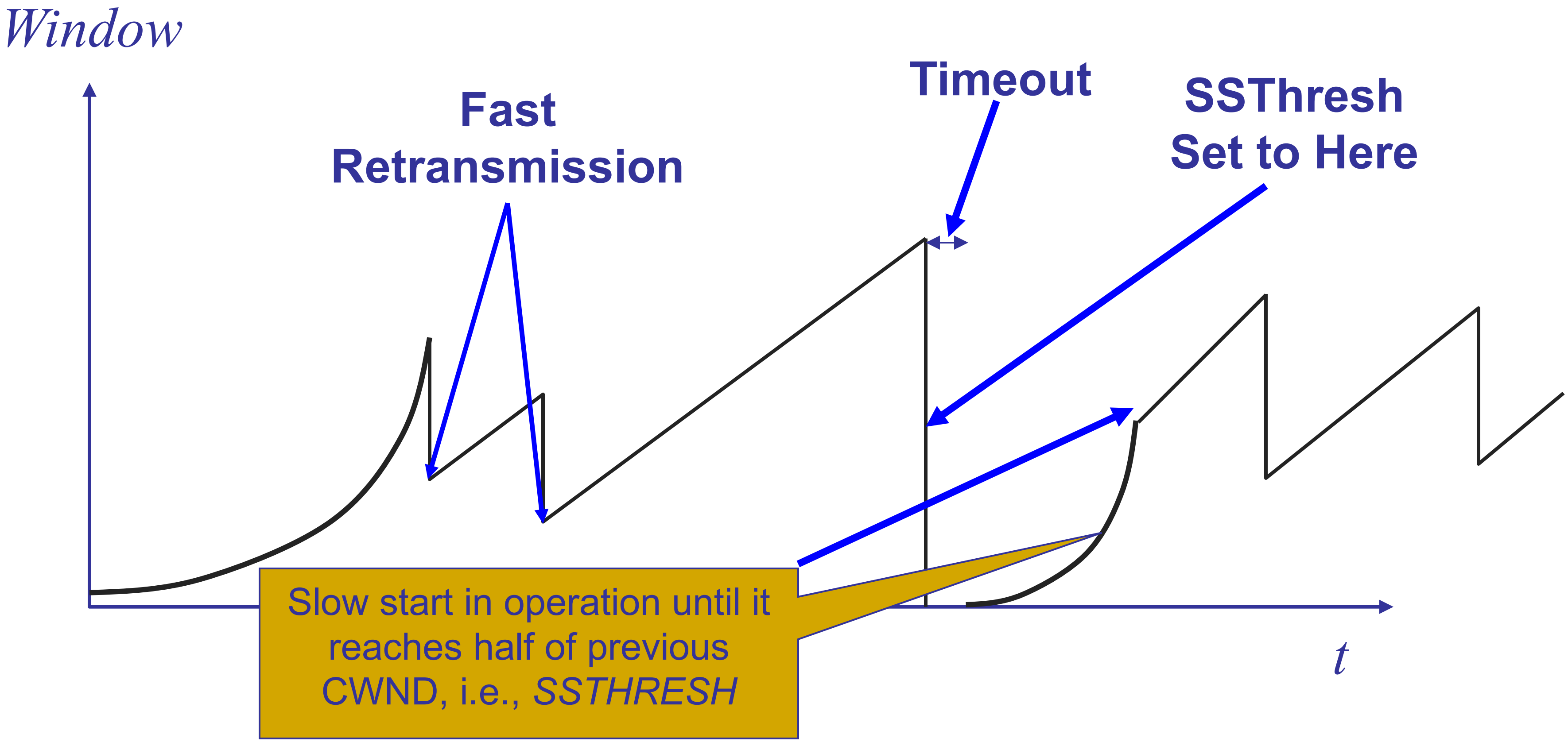
Event: TimeOut

- On Timeout
  - ssthresh ← CWND/2
  - CWND ← 1

Event: dupACK

- dupACKcount ++
- If dupACKcount = 3 /* fast retransmit */
  - ssthresh = CWND/2
  - CWND = CWND/2

Example



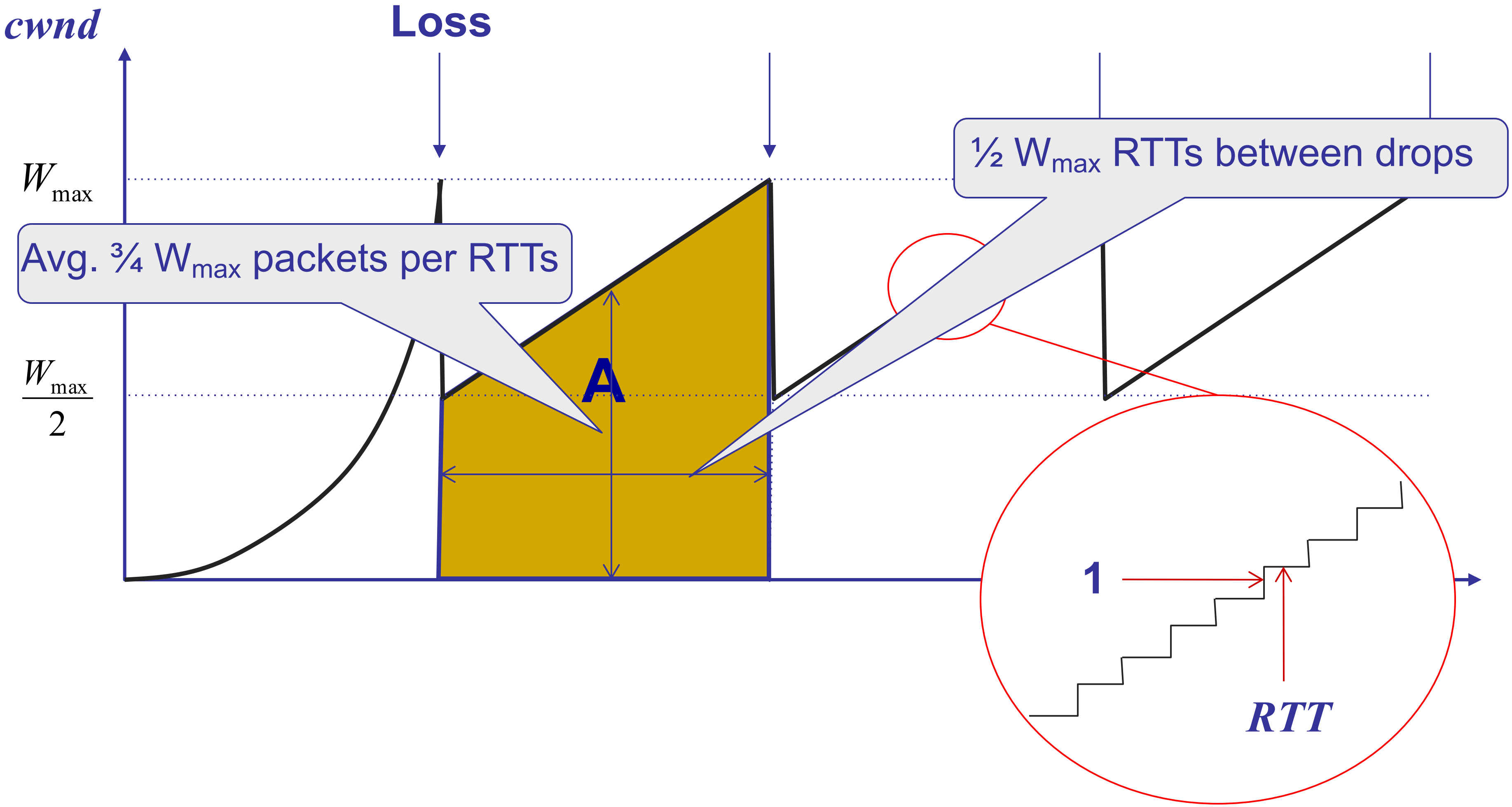
Slow start in operation until it reaches half of previous CWND, i.e., *SSTHRESH*

Slow-start restart: Go back to CWND = 1 MSS, but take advantage of knowing the previous value of CWND

TCP flavors

- TCP-Tahoe
  - CWND =1 on 3 dupACKs
- TCP-Reno
  - CWND =1 on timeout
  - CWND = CWND/2 on 3 dupACKs
- TCP-newReno
  - TCP-Reno + improved fast recovery
- TCP-SACK
  - Incorporates selective acknowledgements

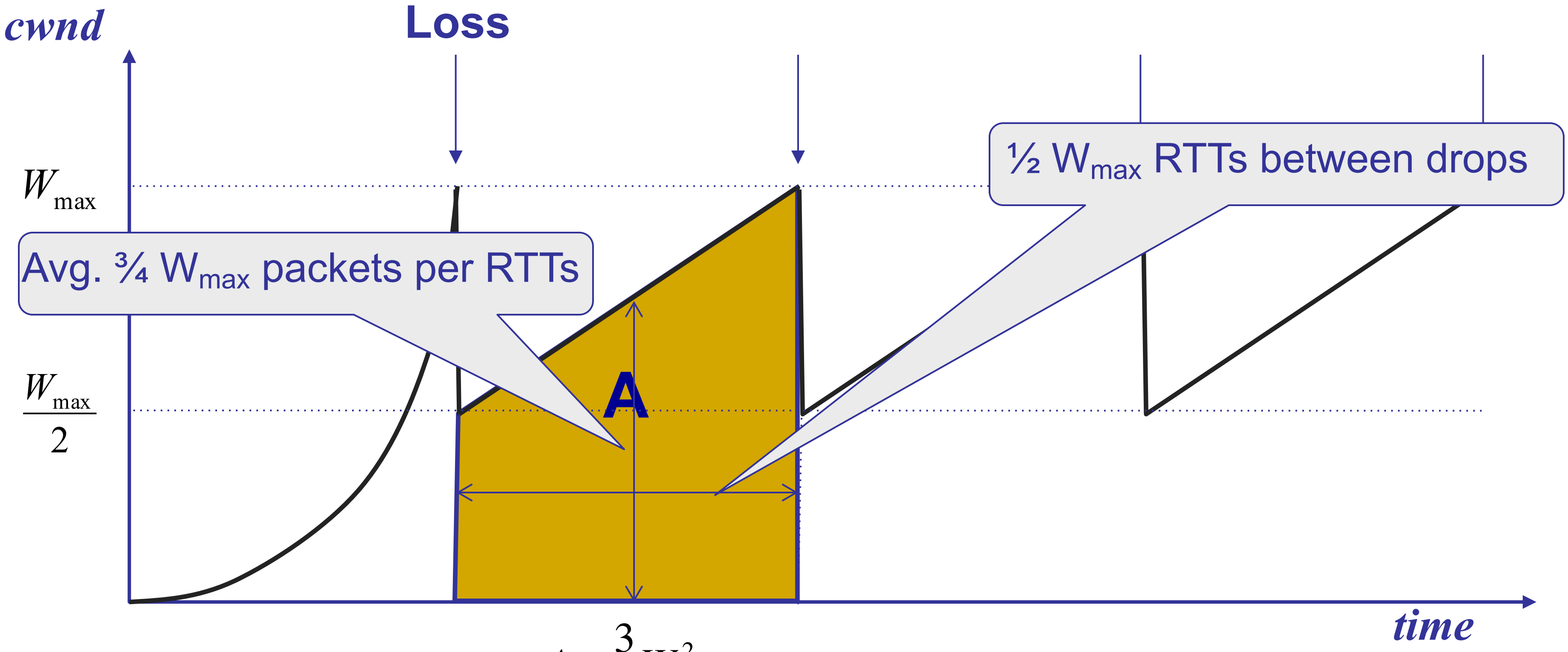
A simple model for TCP throughput



Avg. ¾ W_{max} packets per RTTs

½ W_{max} RTTs between drops

A simple model for TCP throughput



Avg. ¾ W_{max} packets per RTTs

½ W_{max} RTTs between drops

$$A = \frac{3}{8} W_{\max}^2$$

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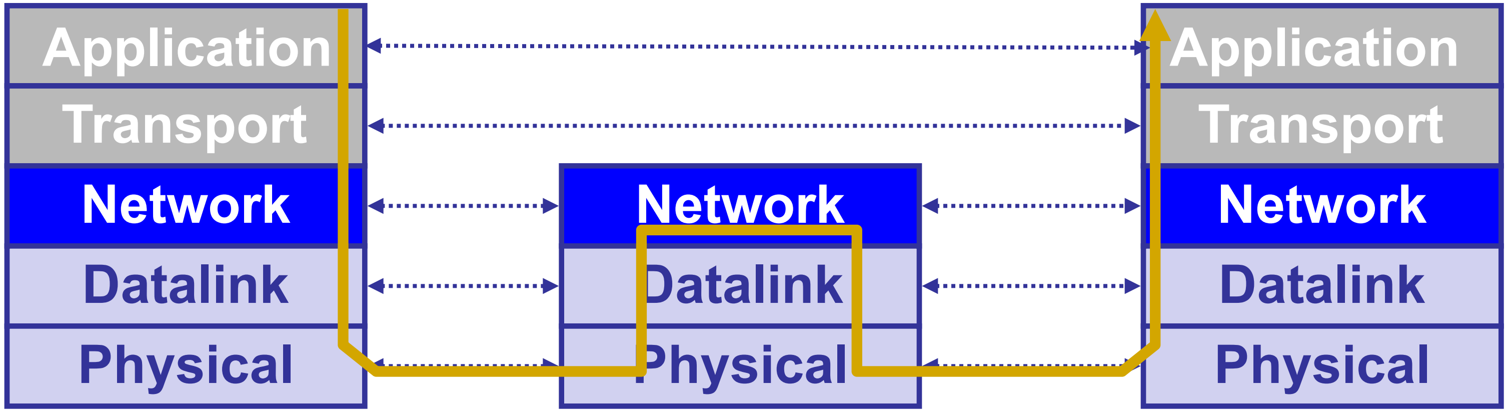
Network layer

- Present everywhere
- Performs addressing, forwarding, and routing, among other tasks



End system Switch End system

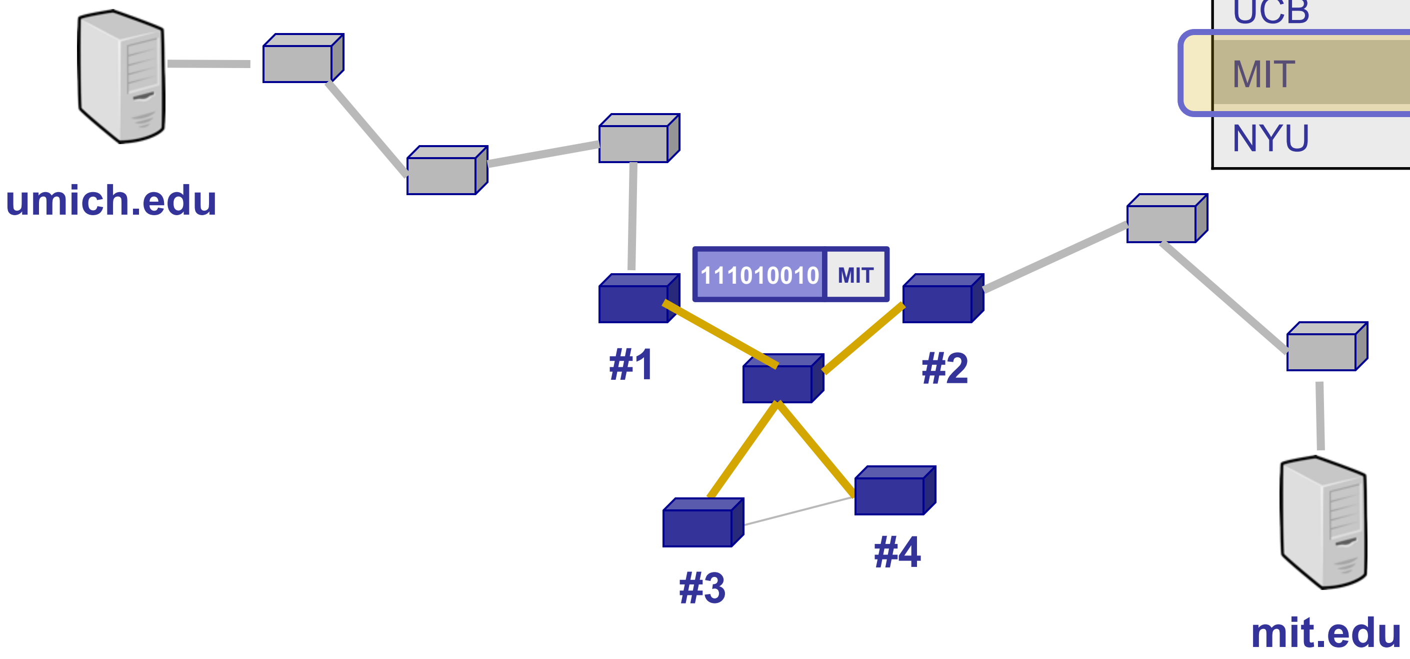
Forwarding vs. routing

- Forwarding: “data plane”
  - Directing one data packet
  - Each router using local routing state
- Routing: “control plane”
  - Computing the forwarding tables that guide packets
  - Jointly computed by routers using a distributed algorithm

Forwarding

Forwarding Table

Destination	Next Hop
UMICH	1
UCB	3
MIT	2
NYU	4



Designing the IP header

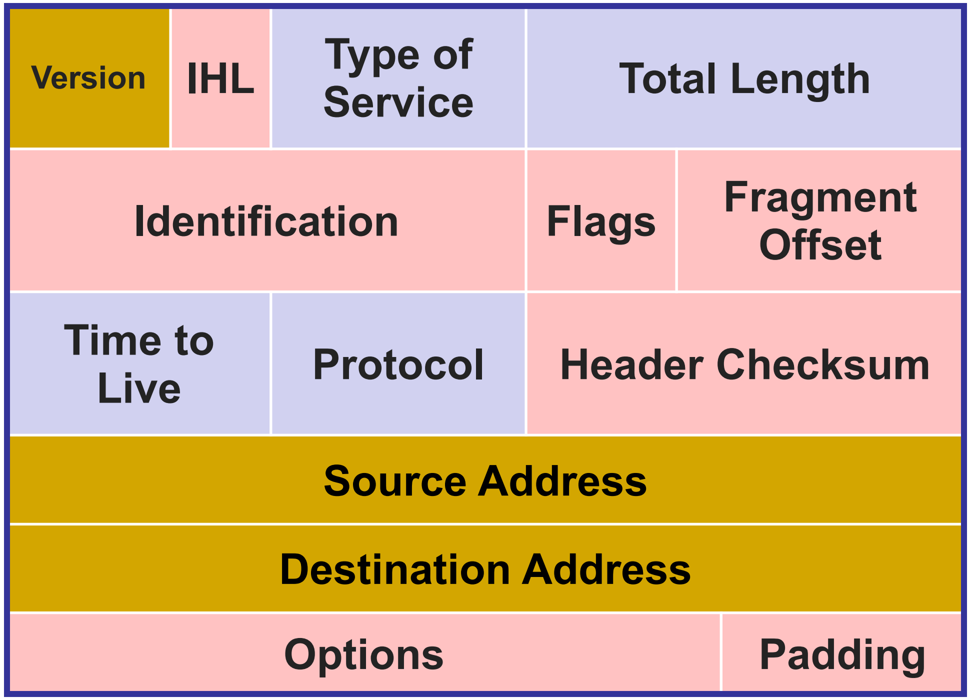
- Think of the IP header as an interface
  - Between the source and destination end-systems
  - Between the source and network (routers)
- Designing an interface
  - What task(s) are we trying to accomplish?
  - What information is needed to do it?
- Header reflects information needed for basic tasks

What information do we need?

- Parse packet
  - IP version number (4 bits), packet length (16 bits)
- Carry packet to the destination
  - Destination’s IP address (32 bits)
- Deal with problems along the way
  - Loops: TTL (8 bits)
  - Corruption: checksum (16 bits)
  - Packet too large: fragmentation fields (32 bits)

IPv4 and IPv6 header comparison

IPv4



Version | IHL | Type of Service | Total Length

Identification | Flags | Fragment Offset

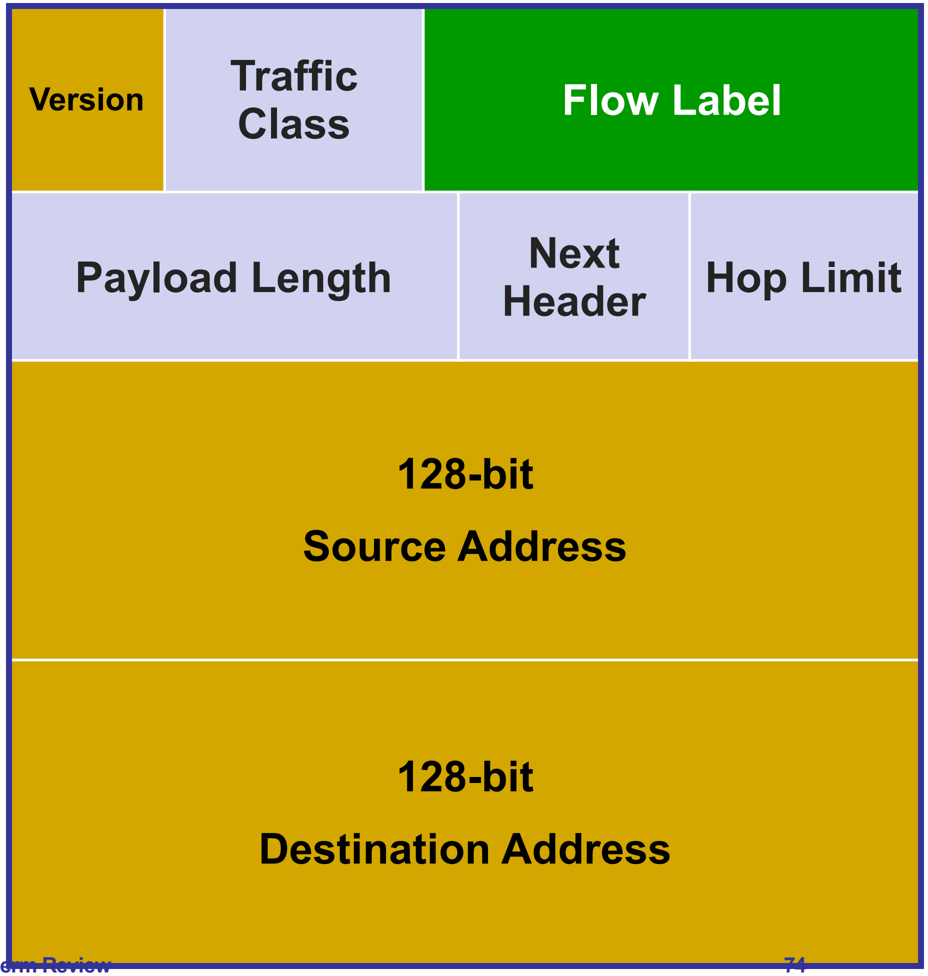
Time to Live | Protocol | Header Checksum

Source Address

Destination Address

Options | Padding

IPv6



Version | Traffic Class | Flow Label

Payload Length | Next Header | Hop Limit

128-bit

Source Address

128-bit

Destination Address

🟨 Field name kept from IPv4 to IPv6

🟥 Fields not kept in IPv6

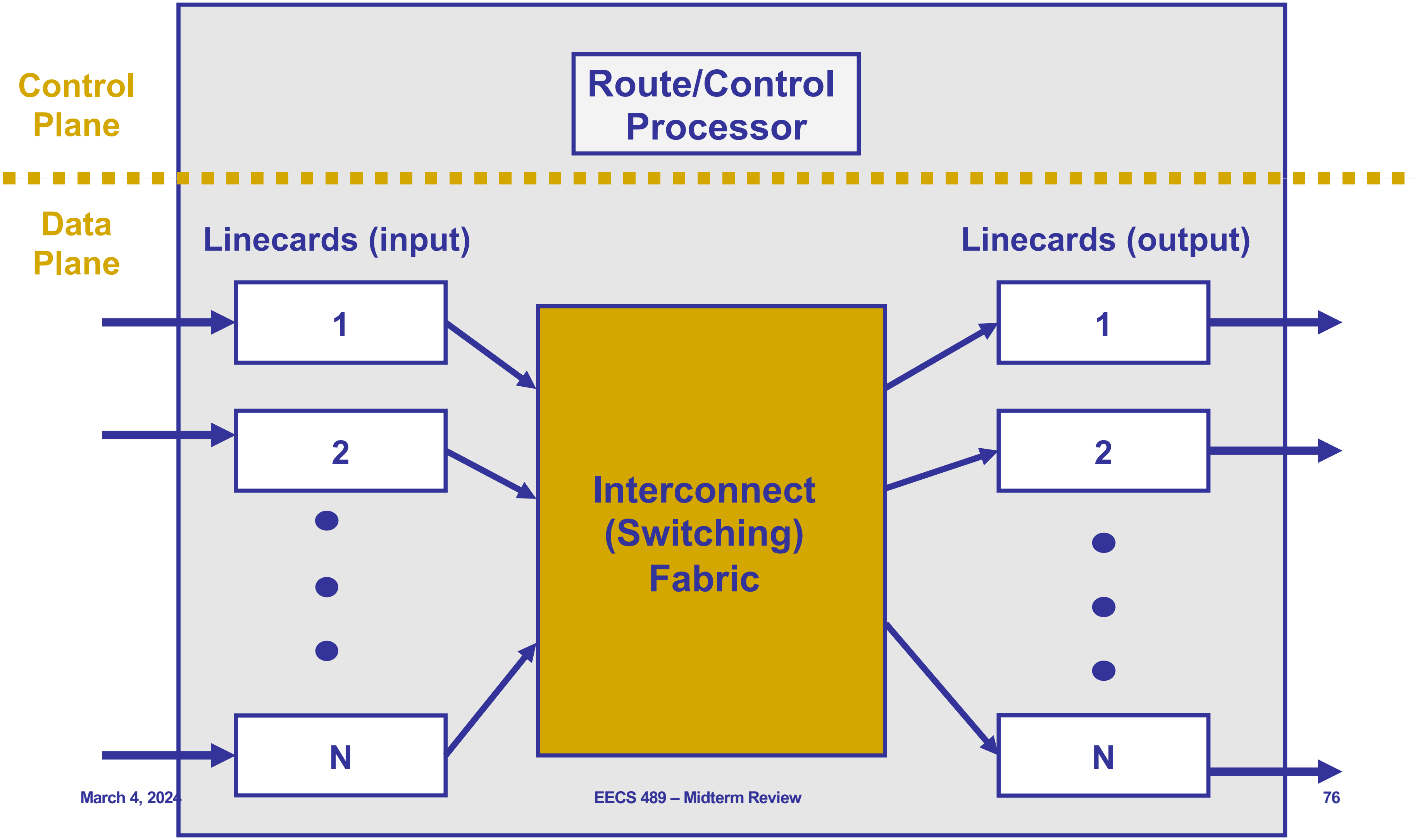
🟪 Name & position changed in IPv6

🟩 New field in IPv6

Philosophy of changes

- Don’t deal with problems: leave it to end points
  - Eliminated fragmentation and checksum
  - Why retain TTL?
- Simplify handling:
  - New options mechanism (uses next header)
  - Eliminated header length
    - Why couldn’t IPv4 do this?
- Provide general flow label for packet
  - Not tied to semantics
  - Provides great flexibility

What's inside a router?



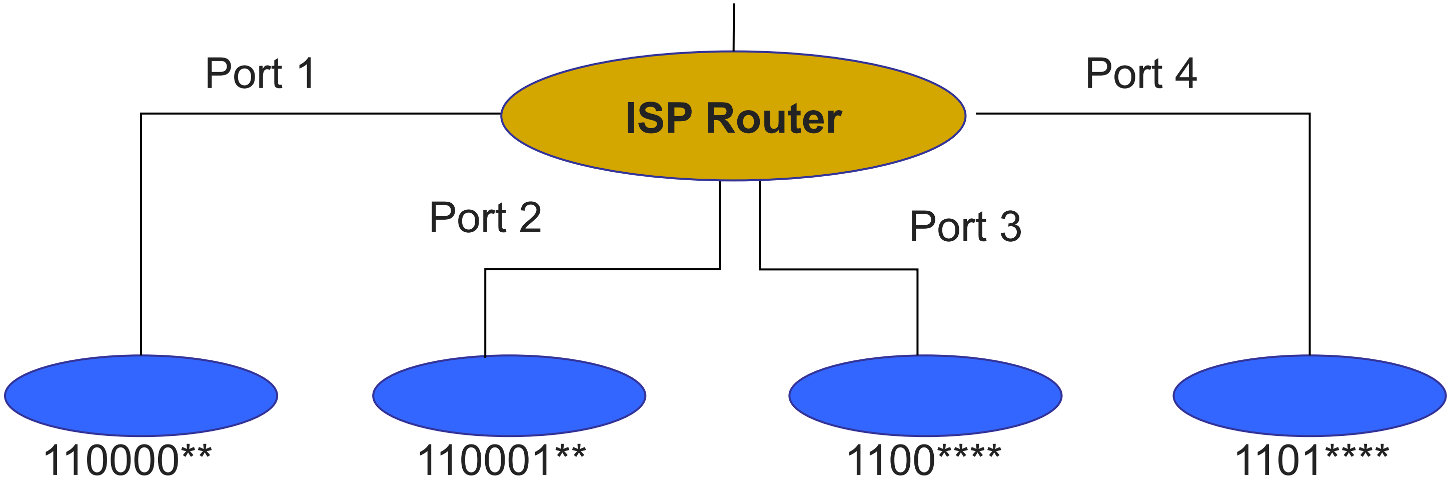
Input linecards

- Main challenge is processing speeds
- Tasks involved:
  - Update packet header (easy)
  - LPM lookup on destination address (harder)
- Mostly implemented with specialized hardware

Looking up the output port

- One entry for each address → 4 billion entries!
- For scalability, addresses are aggregated

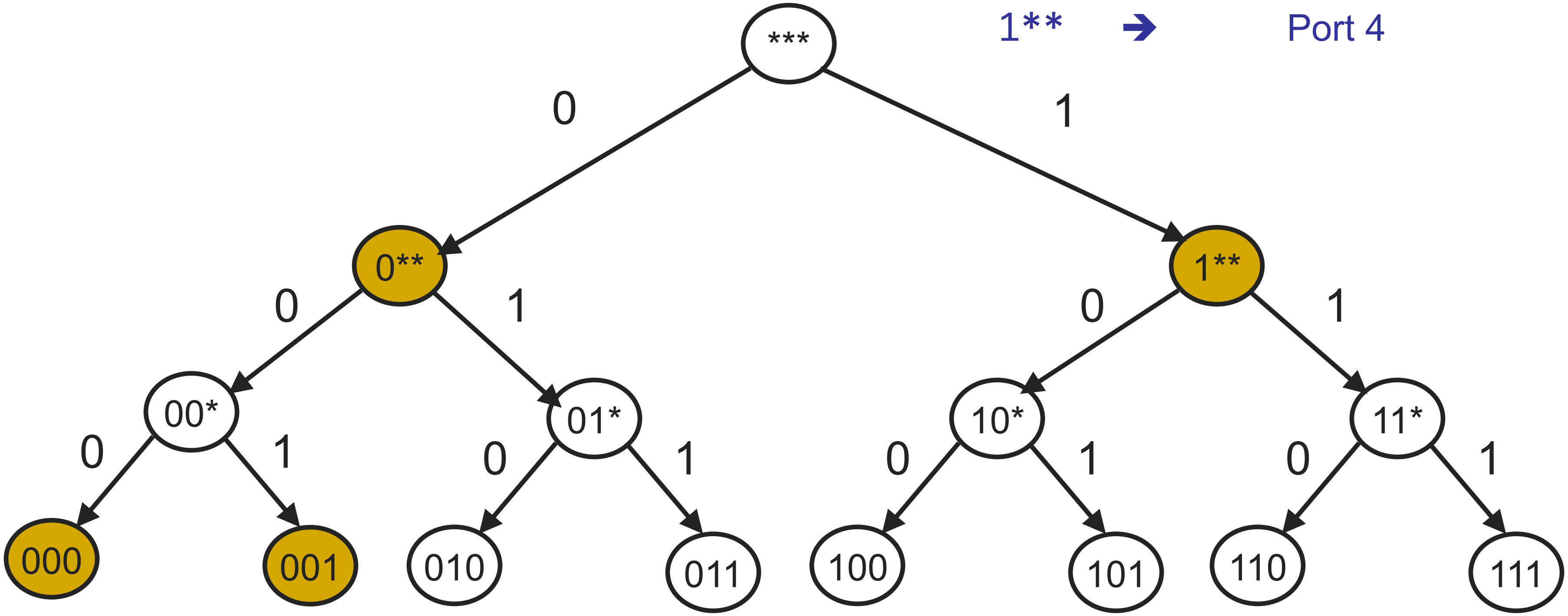
Longest prefix matching



Send to the port with the longest prefix match

Tree structure

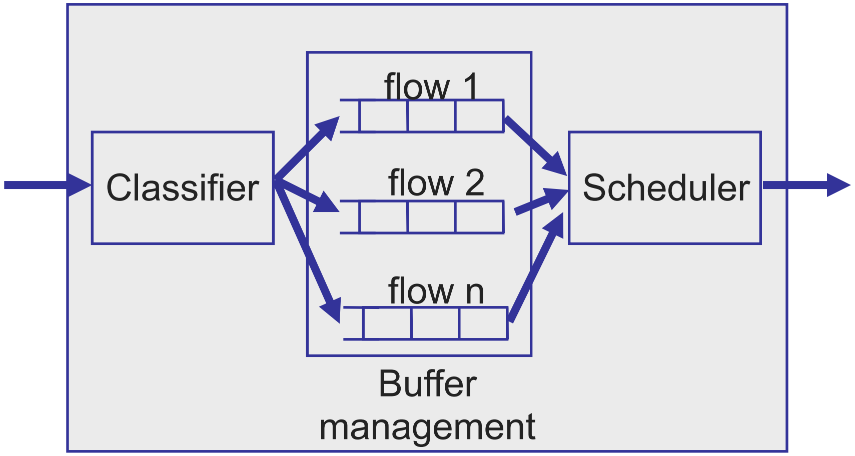
000	→	Port 1
001	→	Port 2
0**	→	Port 3
1**	→	Port 4



Record port associated with latest match, and only override when it matches another prefix during walk down tree

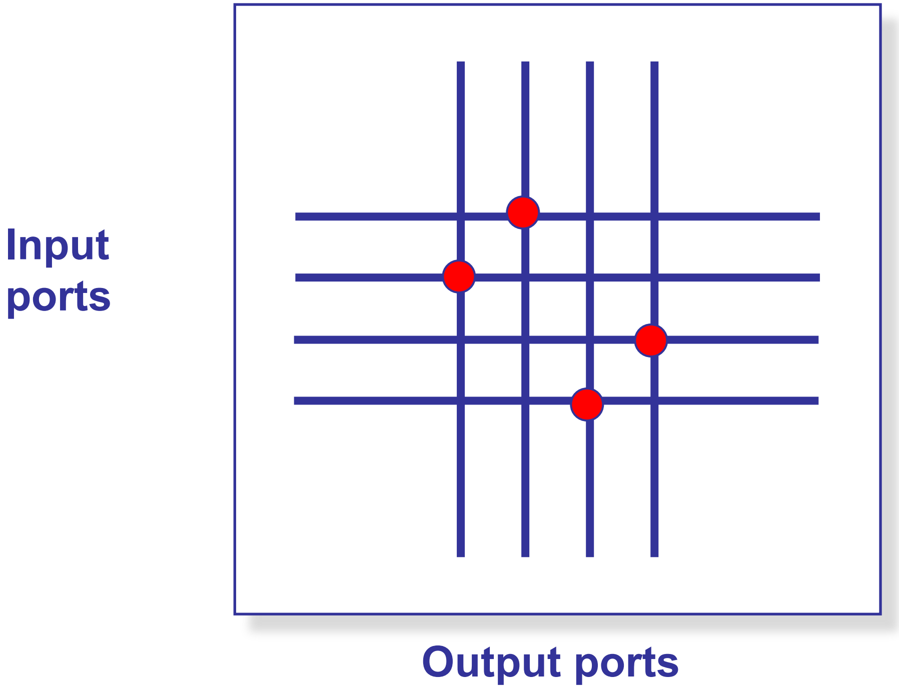
Output linecards

- Packet classification: map packets to flows
- Buffer management: decide when and which packet to drop
- Scheduler: decide when and which packet to transmit



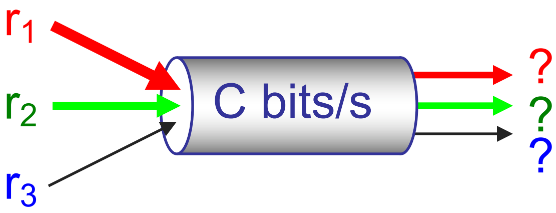
Crossbar interconnect

- 2N buses intersecting with each other:
  - N input
  - N output
- Non-blocking



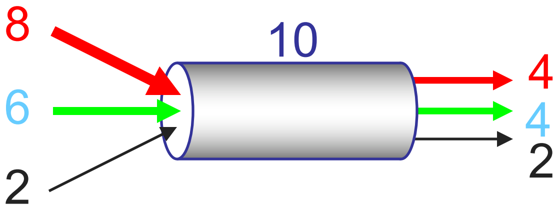
Max-Min fairness

- Given set of bandwidth demands r_i and total bandwidth C, max-min bandwidth allocations are:
  - $a_i = \min(f, r_i)$
  - where f is the unique value such that $\text{Sum}(a_i) = C$



Example

- C = 10; r_1 = 8, r_2 = 6, r_3 = 2; N = 3
- C/3 = 3.33 →
  - r_3 needs only 2
    - Can service all of r_3
  - Remove r_3 from the accounting: C = C – r_3 = 8; N = 2
- C/2 = 4 →
  - Can't service all of r_1 or r_2
  - So hold them to the remaining fair share: f = 4



f = 4:
min(8, 4) = 4
min(6, 4) = 4
min(2, 4) = 2

Max-Min fairness

- Given set of bandwidth demands r_i and total bandwidth C, max-min bandwidth allocations are:
  - $a_i = \min(f, r_i)$
  - where f is the unique value such that $\mathrm{Sum}(a_i) = C$
- If you don’t get full demand, no one gets more than you
- This is what round-robin service gives if all packets are the same size

Summary

- 60-minute midterm exam on canvas
  - **Mar 6**
  - **Available from 9:30AM**
  - **Due at 1PM**

- Demo Exam on Canvas