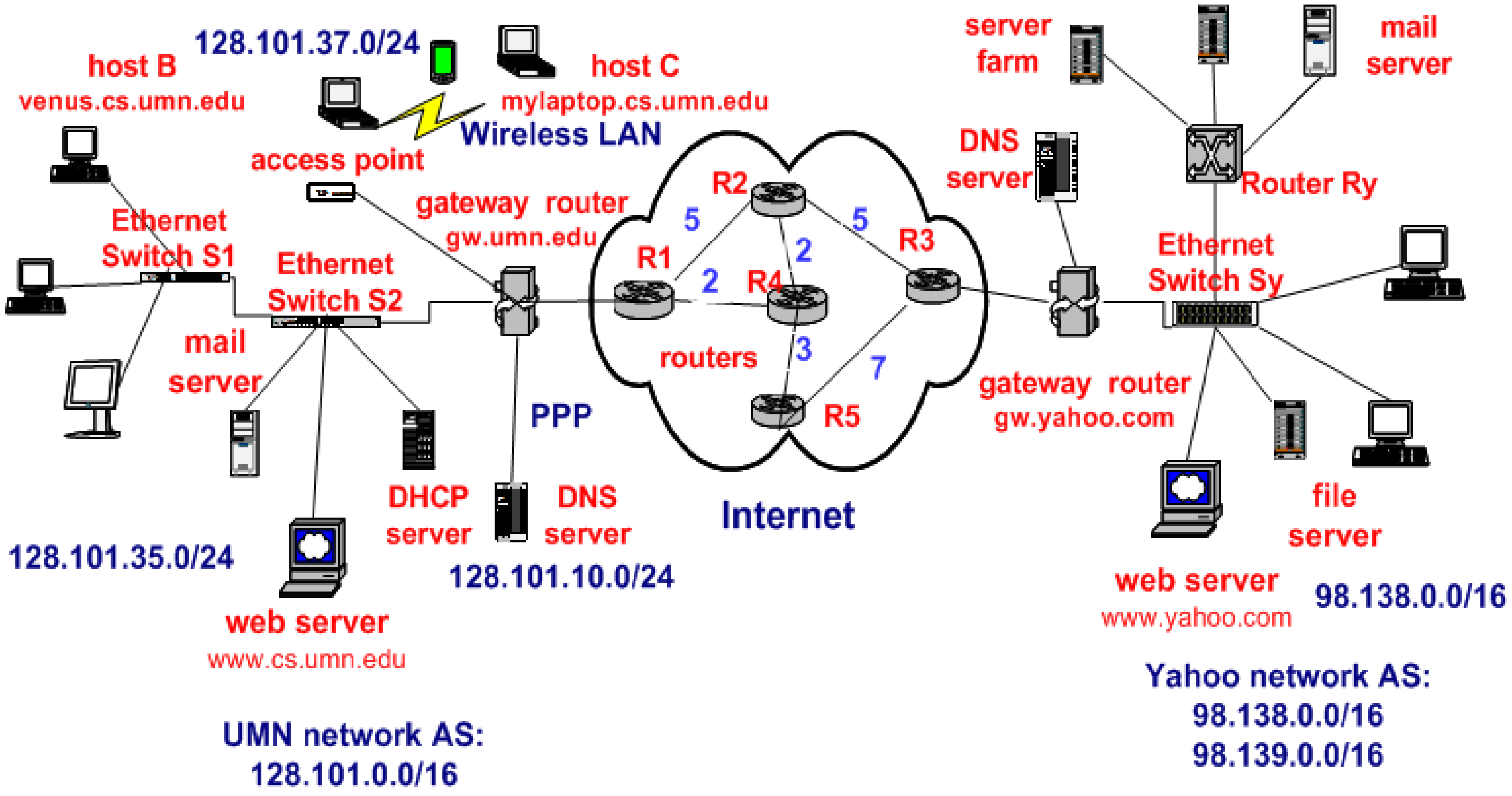
Putting Everything Together

Did you get the whole picture?



Internet:

a huge transformative & disruptive force!

What has become of the Internet:

- Information Service and E-Commerce Platform
  - deliver all kinds of information, news, music, video, shopping
  - web, spotify, iTune, youtube, Netflix, Hulu, …
- Global Information Repository
  - store and search for all kinds of information
  - google, flickr, dropbox, icloud, …
- Cyberspace and Virtual Communities
  - keep in touch with friends and strangers
  - email, facebook, twitter, snapchat, …
- Enormous Super-Computer
  - mobile, cloud computing and services

We're increasingly depending on it!

Within the Internet Core

- Large ISPs with large geographical span

and

- Large content providers with huge data centers

- High capacity, dense and rich topology

- Cloud Computing/Services and Mobile Computing

EDMONTON
SASKATOON
VANCOUVER
VICTORIA
CALGARY
REGINA
WINNIPEG
SEATTLE
PORTLAND
QUEBEC
HALIFAX
MONTREAL
TORONTO
BOSTON
AMSTERDAM
FRANKFURT
LONDON
PARIS
LONDON
STOCKHOLM
SINGAPORE
OSAKA
SACRAMENTO
SAN FRANCISCO
SAN JOSE
SALT LAKE CITY
CHICAGO
KANSAS CITY
ST. LOUIS
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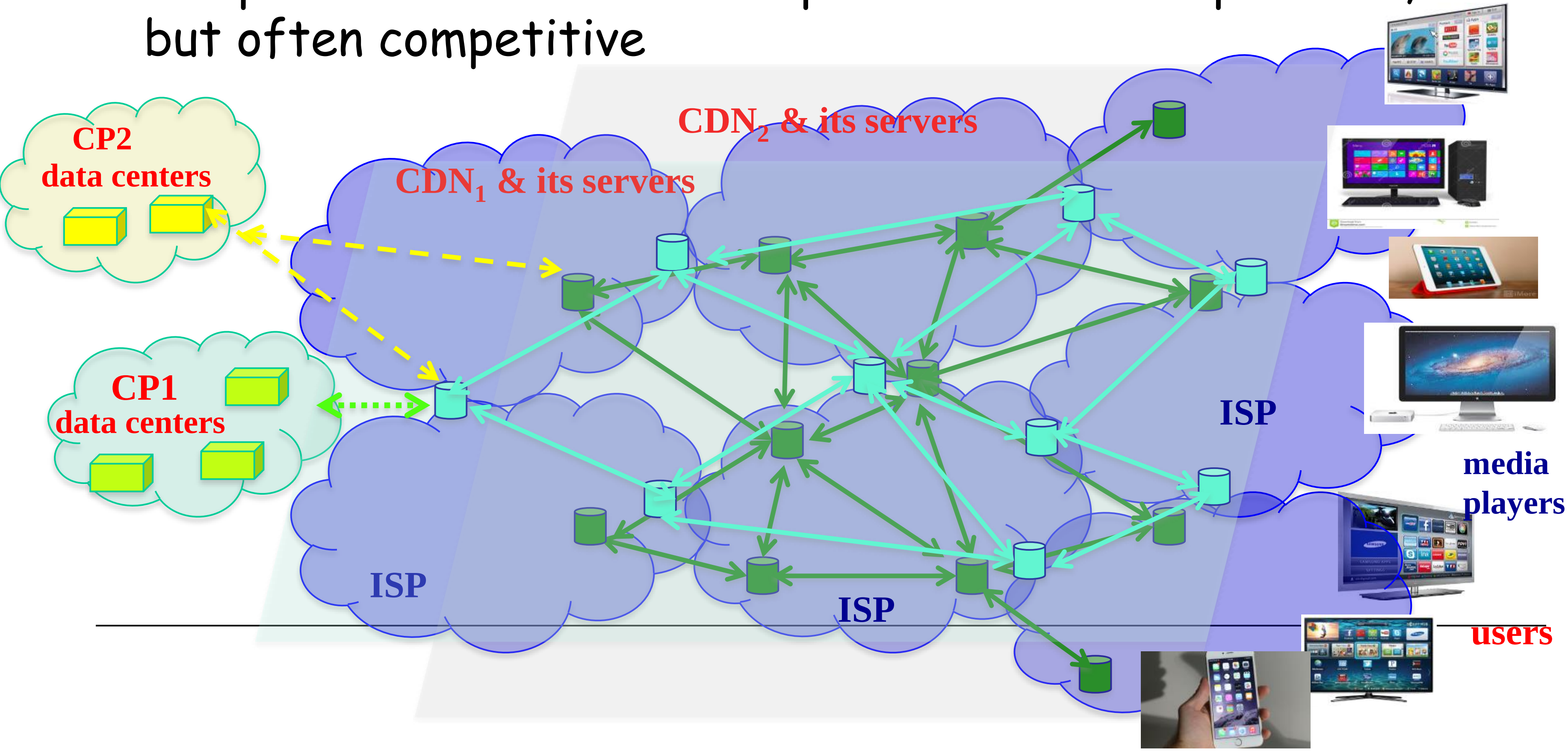
DALLAS
ATLANTA
LONDON
FRANKFURT
AMSTERDAM
HOUSTON
TAMPA
MIAMI
SAN JUAN
HONOLULU

Content Distribution Ecosystem

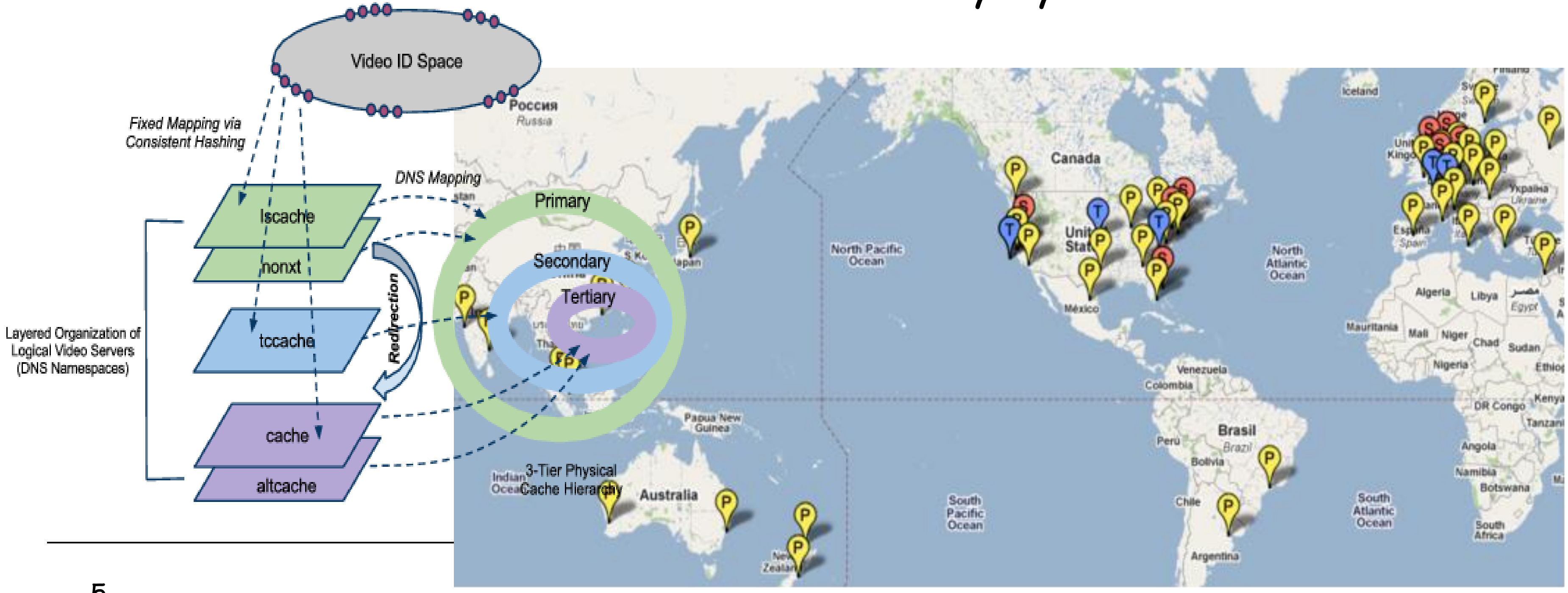
- Multiple major entities involved!
  - content providers (CPs), content distribution networks (CDNs), ISPs and of course, end systems & users
  - some entities may assume multiple roles
- Complex business relationships: sometimes cooperative, but often competitive



Static Content Distribution:

YouTube as a Case Study: world's largest video sharing site

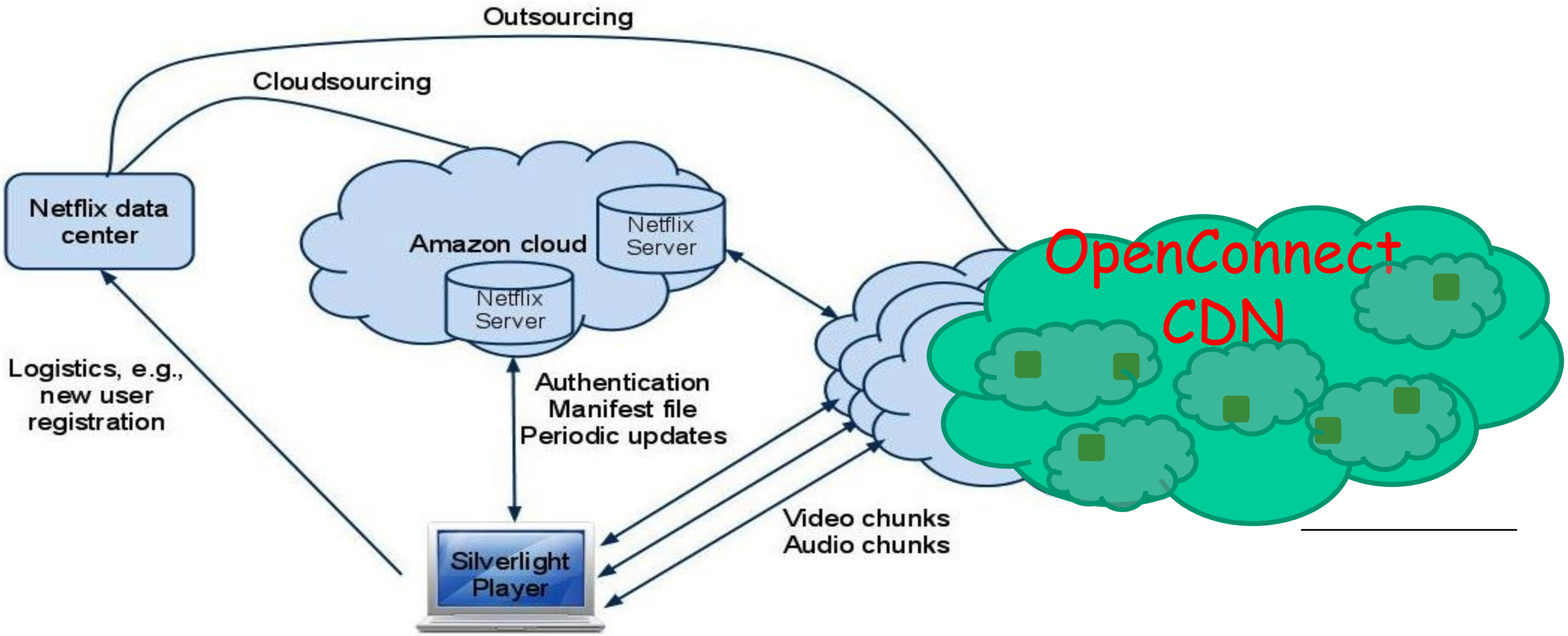
- User interaction with content (e.g., search for a video) is separated from video delivery
- Employs a combination of various "tricks" and mechanisms to scale with YouTube size & handle video delivery dynamics



Static Content Distribution:

Netflix as a Case Study: "first" large-scale cloud-sourcing success

- Has its own "data center" for certain crucial operations (e.g., user registration, …)
- Most web-based user-video interaction, computation/storage operations are cloud-sourced to Amazon AWS
- Users need to use MS Silverlight or other players for video streaming
- Video delivery was/is partly out/cloud-sourced to 3 CDNs;
- but now most utilizes its "own" OpenConnect boxes placed at participating ISPs, forming its own CDN



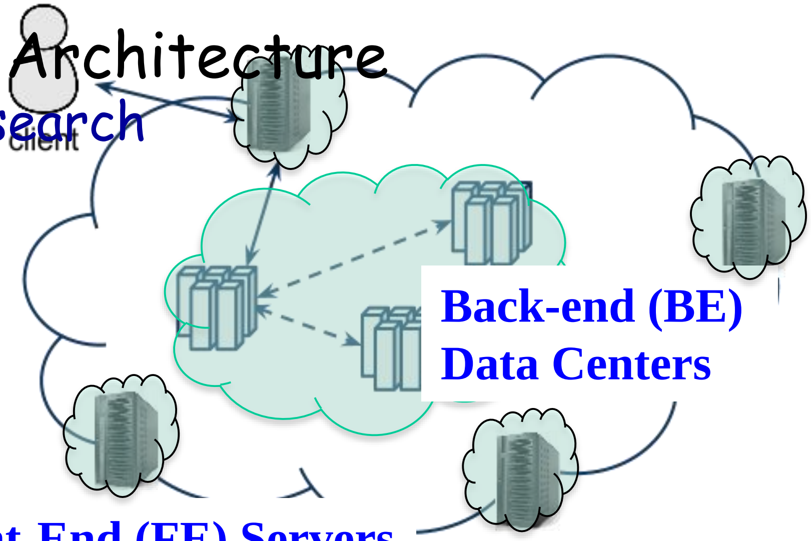
Dynamic Content Distribution

- Web search as (dynamic) content delivery – e-commerce, social networking services have similar architectures
  - response contains both static content (e.g., banner, css files) and dynamically generated search response (dynamic content)
- User QoE metric: end-to-end *search response time* (SRT)
- Generic Web Search System Architecture
  - backend data centers processing search queries & generating responses
  - front-end edge servers (CDN) handling search query delivery

➢ Google: deploy its own CDN

➢ Bing: utilized Akamai CDN (it now also builds its own CDN)

➢ Amazon and Facebook have also built its own CDNs



Back-end (BE) Data Centers

Front-End (FE) Servers (Edge Cloud/CDN)

Data Center Networks

- 10's to 100's of thousands of hosts, often closely coupled, in close proximity:
  - e-business (e.g. Amazon)
  - content-servers (e.g., YouTube, Akamai, Apple, Microsoft)
  - search engines, data mining (e.g., Google)

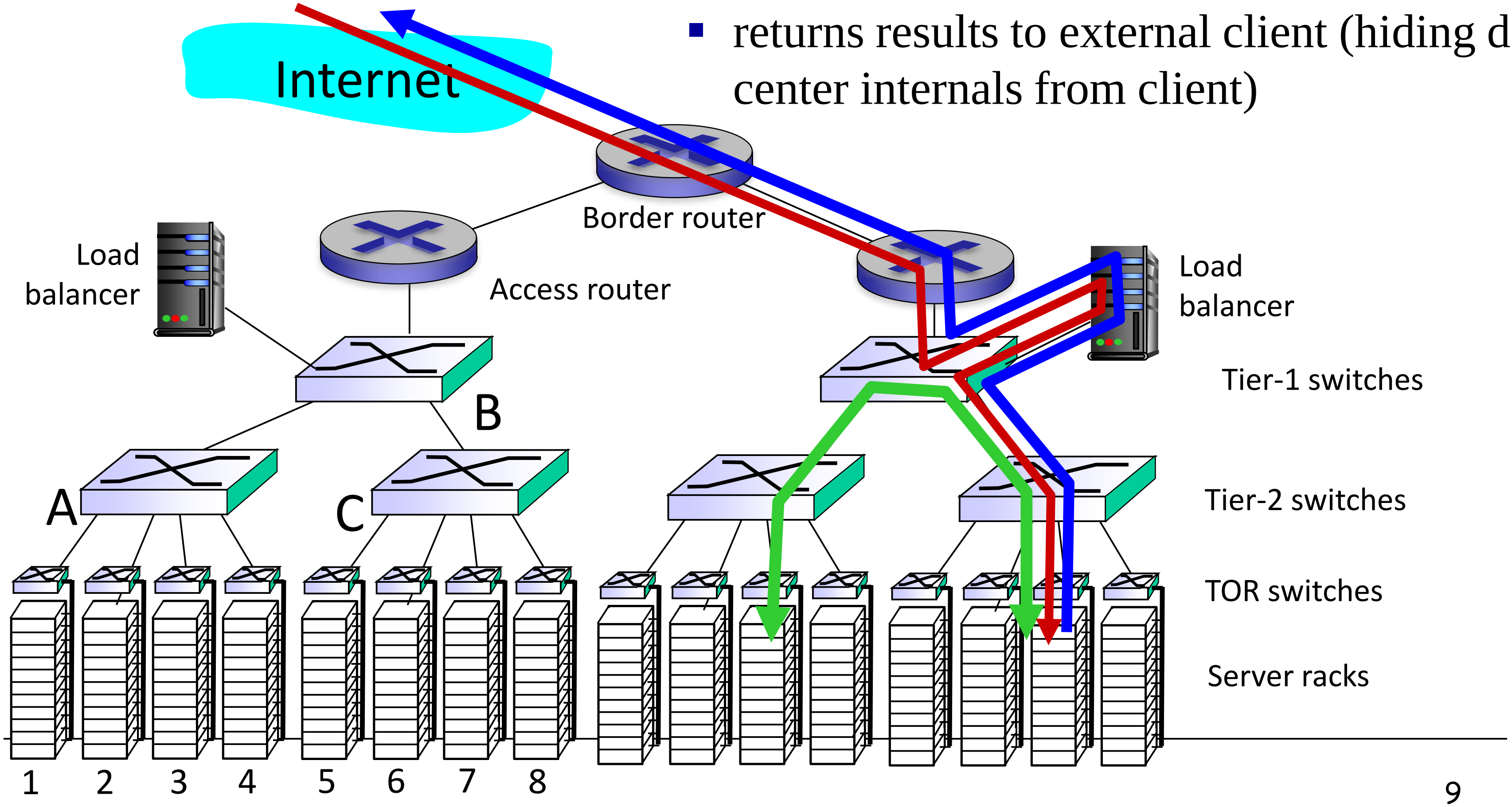
- challenges:
  - multiple applications, each serving massive numbers of clients
  - managing/balancing load, avoiding processing, networking, data bottlenecks

Inside a 40-ft Microsoft container, Chicago data center

Data center networks

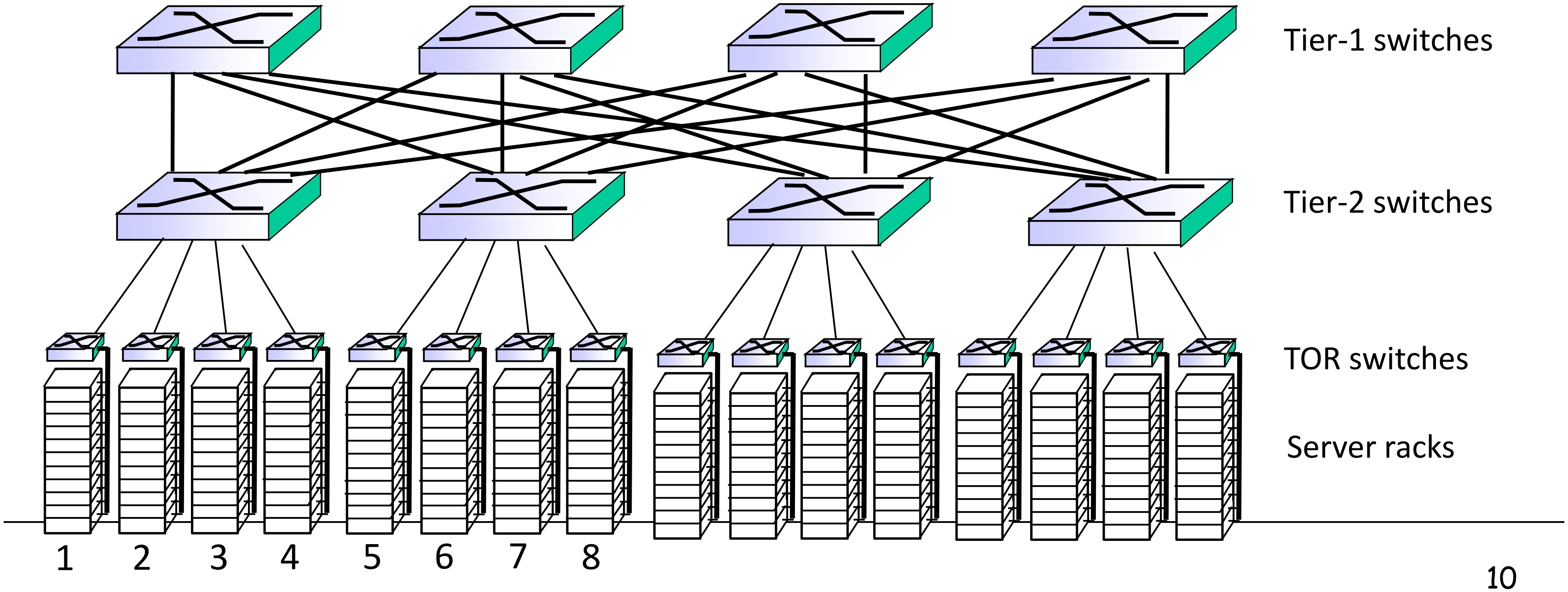
load balancer: application-layer routing

- receives external client requests
- directs workload within data center
- returns results to external client (hiding data center internals from client)

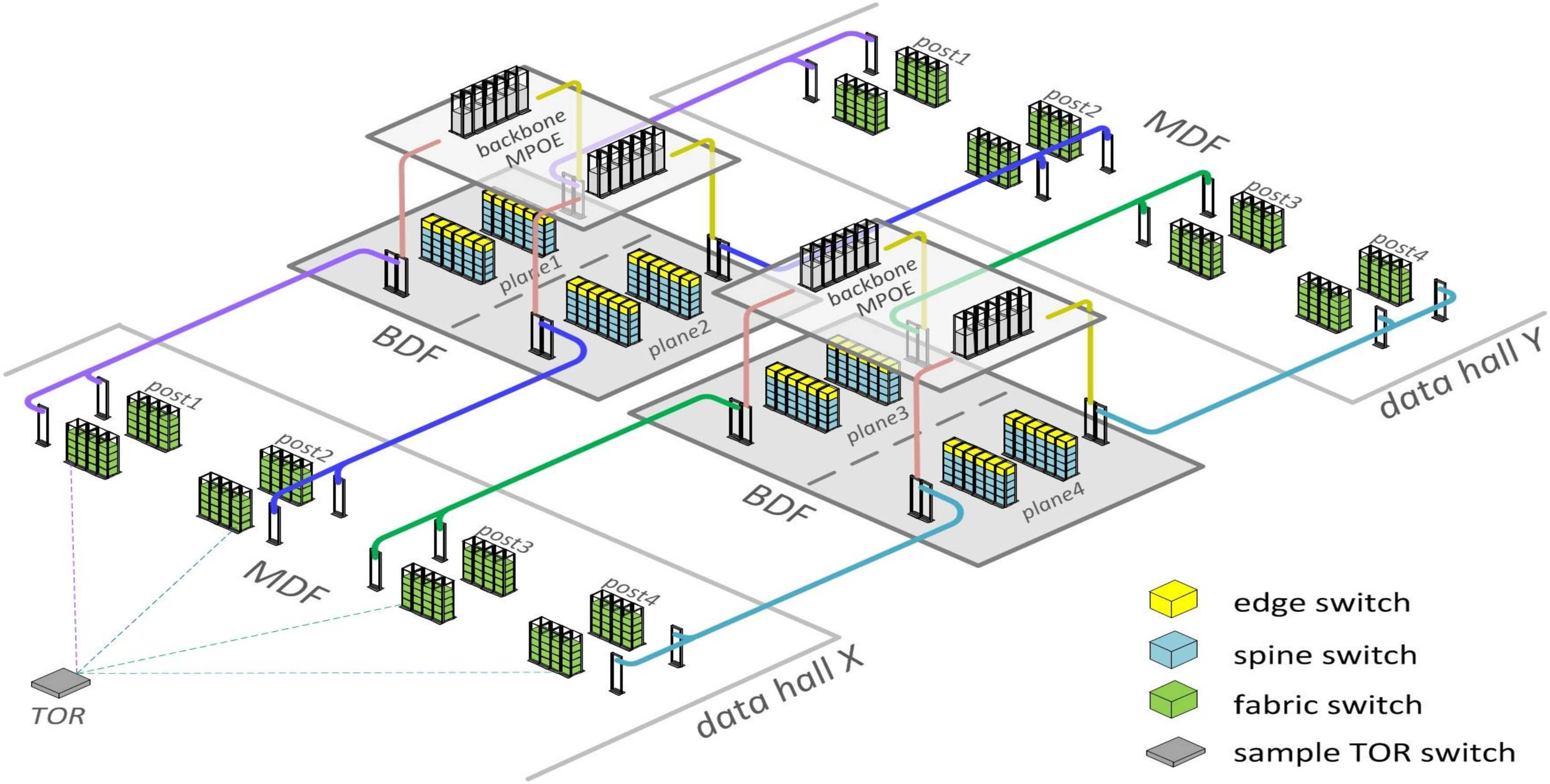


Data center networks

- rich interconnection among switches, racks:
  - increased throughput between racks (multiple routing paths possible)
  - increased reliability via redundancy

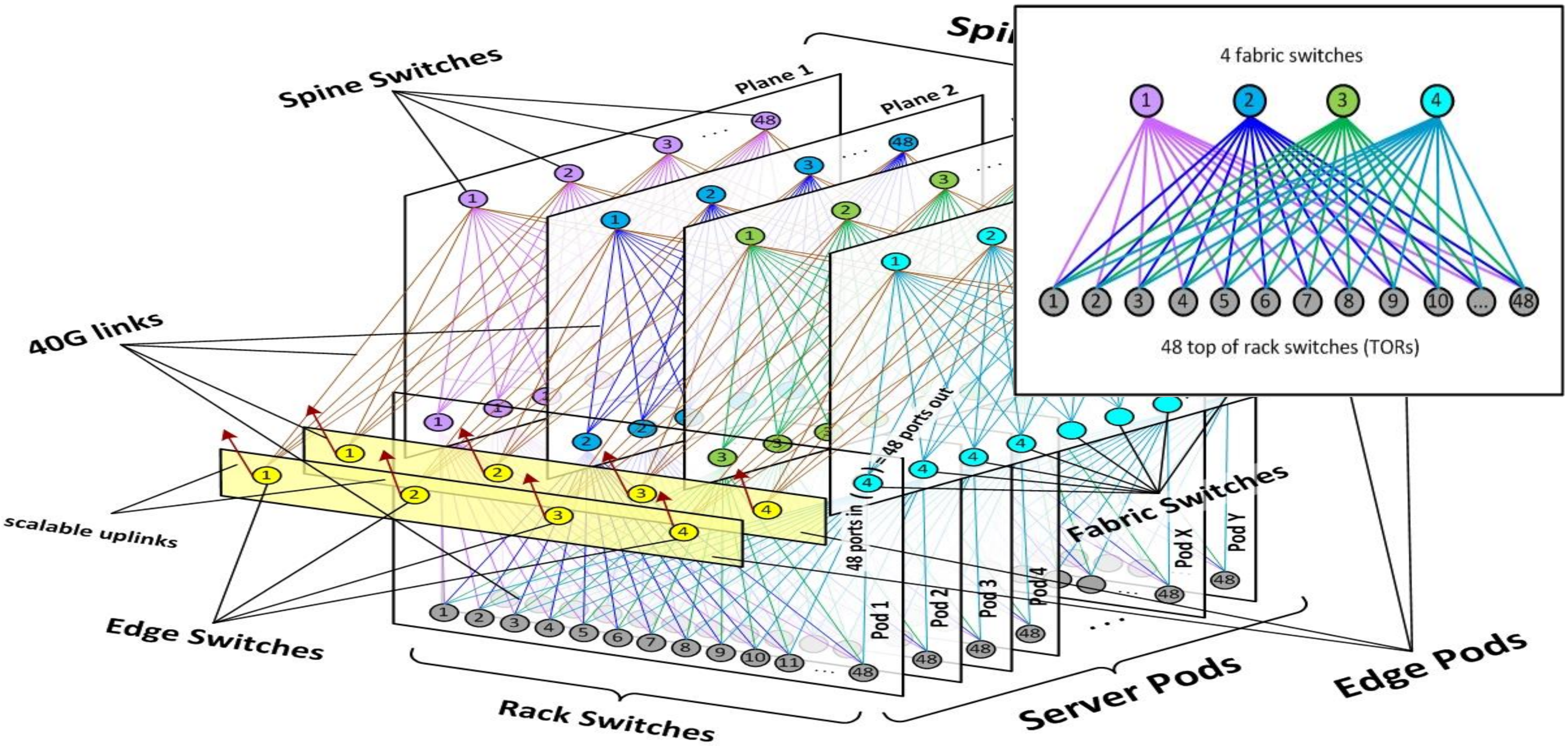


Facebook Data Center Fabric



https://code.facebook.com/posts/360346274145943/introducing-data-center-fabric-the-next-generation-facebook-data-center-network/

Facebook Data Center Fabric



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Putting Everything Together

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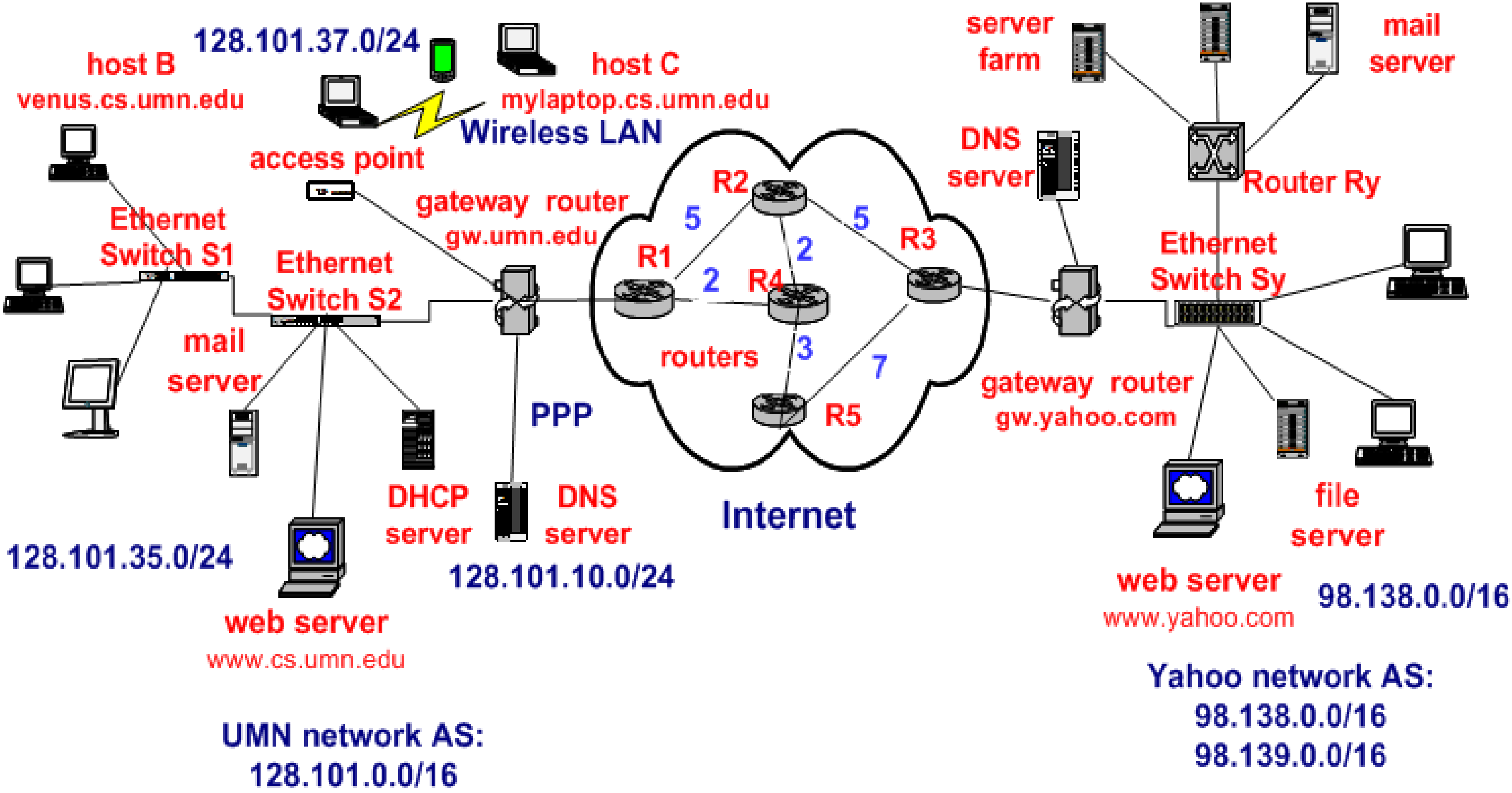


A Quick Review of What We Learned

Basic concepts in computer networks

- packet switching & statistical multiplexing
- protocols and layered architecture
- fundamental issues in networking
    - distributed & complex system
        - addressing, protocols, …
    - many things can go wrong: error, loss, …
    - correct operations, efficiency of protocols

- Application Layer
    - application requirements & transport services
    - client-server vs. peer to peer paradigms
    - domain name system and DNS (name vs. address)

A Quick Review of What We Learned…

- Transport Layer: basic functions & services
  - multiplexing and de-multiplexing
  - UDP: connectionless transport service
    - src/dst port no.'s, checksum
  - TCP: connection-oriented, reliable service
    - TCP segment format, seq./ack. no, "flags"
    - connection set-up and tear down
  - reliable data transfer protocols
    - stop-&-wait, Go-back-N, selective repeat
- Network Layer: basic functions & services

  end-to-end data delivery: addressing, routing & forwarding

  - network data plane vs. control plane
  - data plane: layer 3 routers (and also layer 2 switches)
  - IP addresses: network part (net prefix) vs. host part

A Quick Review of What We Learned …

- How to obtain an IP address: how does DHCP work?
- Network service models: datagram vs. virtual circuit
- IP Forwarding: datagram model
  - forwarding within vs. outside an IP subnet: *How does a host know whether a destination is within or outside its subnet? n*
  - within same IP network:
    - direct forwarding using data link layer
      - need to know MAC address of destination: ARP!
  - Outside its own IP network:
    - forward to its (default) router:
      - need to know router's MAC address
    - router looks up its routing table (using longest prefix matching), and forwards to other routers if necessary; a packet finally reaches its destination host

Understanding interaction with data link layer important!

A Quick Review of What We Learned …

- IP datagram format
  - source and destination IP addresses
  - IP datagram id, offset, length, "fragment flags"
    - why IP fragmentation may be necessary
      - link and path MTUs
    - how fragmentation and reassembly done
      - how these fields are used
    - TTL, header checksum, IP options, …
  - ICMP protocol:
    - When are ICMP messages generated
    - What ICMP messages are used for
      - error/info reporting to source, ICMP redirect, …
- Virtual Circuit: how to set up a VC?
  - incoming and outgoing VCI numbers, input/output ports
  - MPLS (multi-protocol label switching)

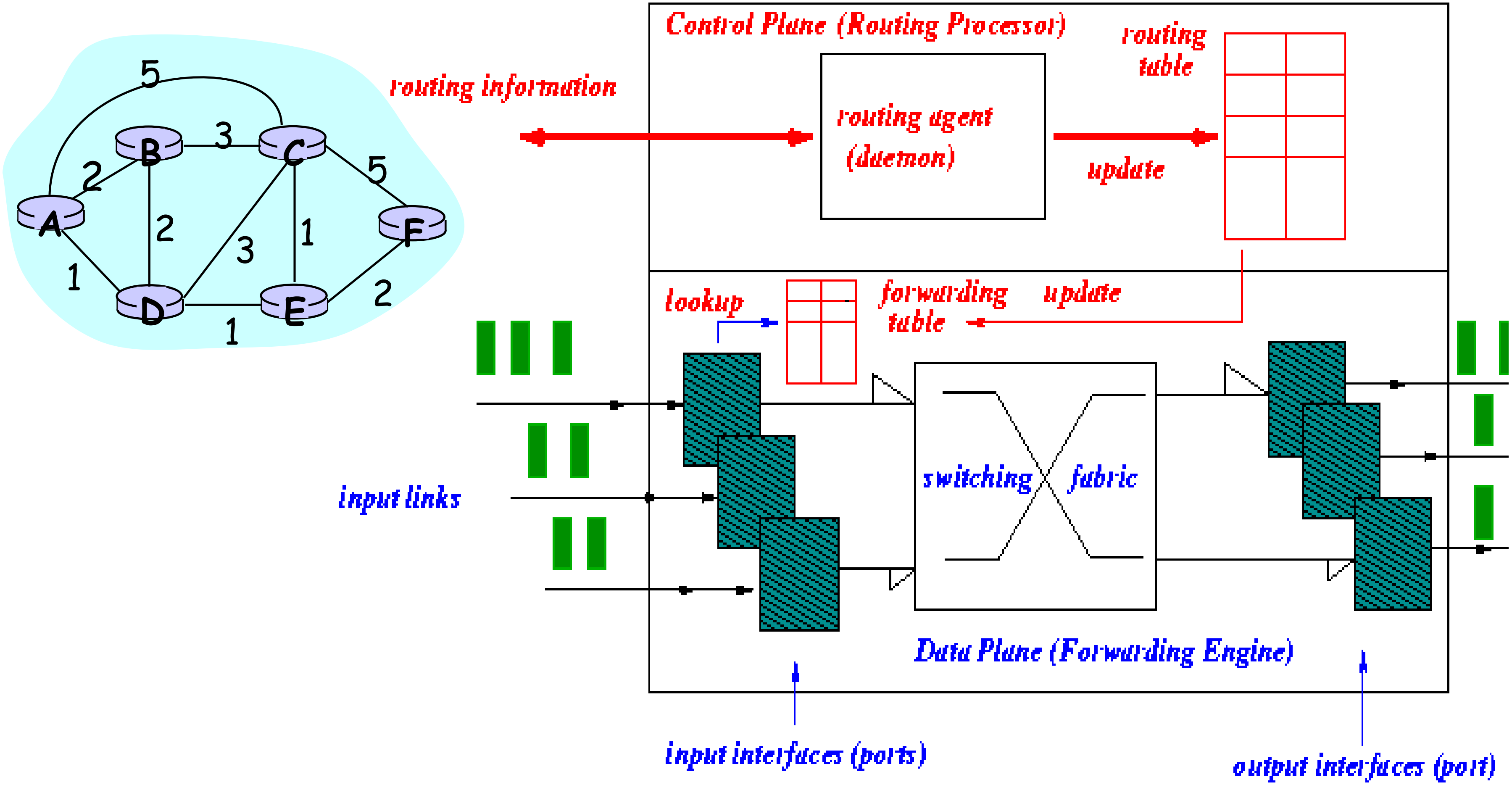
A Quick Review of What We Learned …

- Network Control Plane: centralized vs. distributed
  - (Distributed) Network Routing: basic issues
    - two distributed routing algorithms

      link state vs. distance vector

      - routing information exchanged
      - how shortest paths computed
      - how routing tables constructed
      - count-to-infinity problem in DV
  - SDN and Centralized Control Plane: Openflow switches and SDN controllers
- Routing in Internet
  - scaling issues and hierarchical routing
    - inter-domain vs. intra-domain routing
  - Intra-domain routing protocols: RIP, OSPF
  - Inter-domain: BGP and policy routing
    - customer-provider vs. peering relationships

Routing & Forwarding:
Logical View of a Router



routing information

Control Plane (Routing Processor)

routing agent (daemon)

update

routing table

lookup

forwarding table

update

input links

switching fabric

Data Plane (Forwarding Engine)

input interfaces (ports)

output interfaces (port)

A Quick Review of What We Learned …

- Data Link Layer : basic services and functions

  data delivery over a link: framing, access control, error checking, …

  - MAC addresses (typically 48 bits)
    - flat addressing: hexadecimal notation, 45:AF:00:FF:12:01
    - unicast vs. broadcast: how adapter deals with MAC addr.?
  - Address resolution and ARP
    - why do we need ARP? (see previous slide)
    - how does ARP work?
    - how are ARP messages delivered?

    Interaction between IP layer and data link layer!
  - Broadcast local area network & media access control
    - Why do we need media access control (MAC?)
      - shared media: issues and difficulties
      - addressing (MAC addresses)
    - Taxonomy of MAC mechanisms

A Quick Review of What We Learned …

- Data Link Layer …:
  - Random access control:
    - ALOHA vs. slotted ALOHA
    - CSMA vs. CSMA/CD (carrier sensing, collision detection)
  - Adaptive (on-demand) controlled access:
    - token passing vs. polling

    Efficiency of MAC protocols: light vs. heavy load
  - Ethernet
    - CSMA/CD, exponential random back-off
      - how does it work? basic algorithm
    - Some important concepts:
      - collision domain & network diameter
      - bit time, slot time (512 bit time)

      Why does Ethernet have a min. frame size constraint?
    - Ethernet frame format
    - 10BaseT, 100BaseT (Fast Ethernet), Gigabit Ethernet

A Quick Review of What We Learned …

- Data Link Layer …:
  - 802.11b and Wireless LAN:
    - key issues & difficulties:
      - hidden terminal problem, power saving requirement
    - receiver acknowledgement needed!
      - how does it work? SIFS < DIFS
    - CSMA/CA:
      - how does it work? RTS, CTS, NAV
  - PPP: point-to-point link layer protocol, byte stuffing
  - Bridging: connecting multiple LAN segments
    - basic functions: forwarding/filtering frames
    - bridge forwarding table & self-learning
    - looping issue: bride spanning tree
- Special Networking Devices we have encountered:
  - repeaters (hubs), bridges/(layer 2) switches, routers

    What are their functions, and how do they work?

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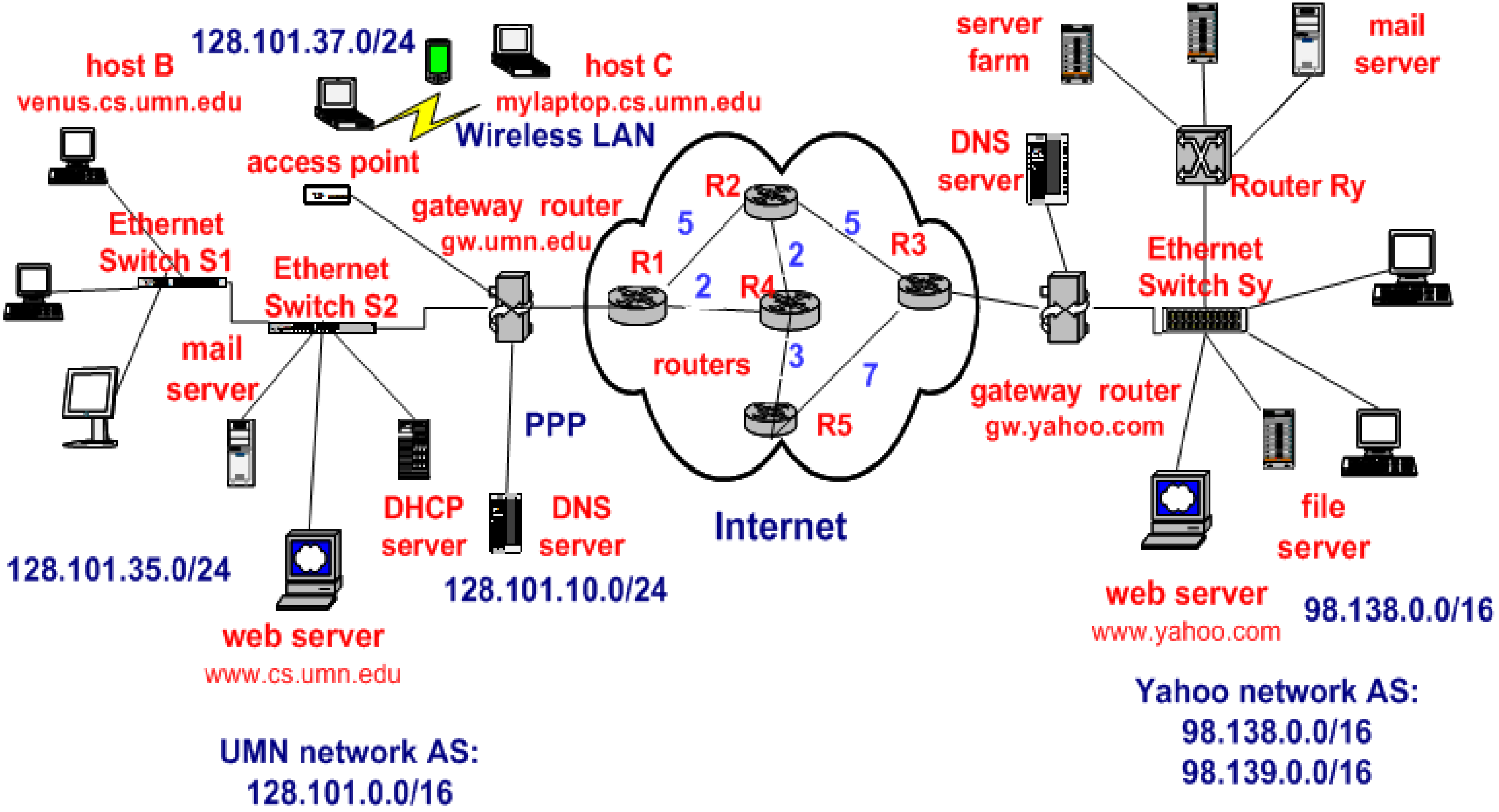

Putting Everything Together…

Walk through the whole picture, and do the following "gedanken" experiments, thinking about

- operations performed at hosts/servers
  - source host, destination host (web, mail servers, …)
  - Internet infrastructure servers (DNS, DHCP, …)
- addressing information at each layer
- interaction between the layers (e.g.,various protocols used)
- operations performed by hubs, bridges/switches, routers
  - what information maintained by each device, how do they get the information? what actions do they perform?

- how host A downloads a web page from web server www.cs.umn.edu?
- how host A telnets to host B?
- how host C accesses the mail server mail.cs.umn.edu?
- how host A downloads a web page from web server www.yahoo.com?
- how host A accesses his/her email at his/her yahoo mail account?
- how host C sends, say, an instant message, to a user logged on at host X?