Light at the end of the tunnel

Final Lecture: Course Overview

Acknowledgments: Lecture slides are from Computer networks course thought by Jennifer Rexford at Princeton University. When slides are obtained from other sources, a reference will be noted on the bottom of that slide and full reference details on the last slide.

Goals of Today's Class

- What are the key concepts in networking?
  - Hierarchy, indirection, caching, randomization
  - Soft state, layering, (de)multiplexing, e2e argument
- Why was there no math in this course?
  - Is theory even useful in data networking?
  - Control theory, graph theory, game theory, optimization theory, queuing theory, scheduling theory, …
- What's going to happen to the Internet?

Key Concepts in Networking

Networking Has Some Key Concepts

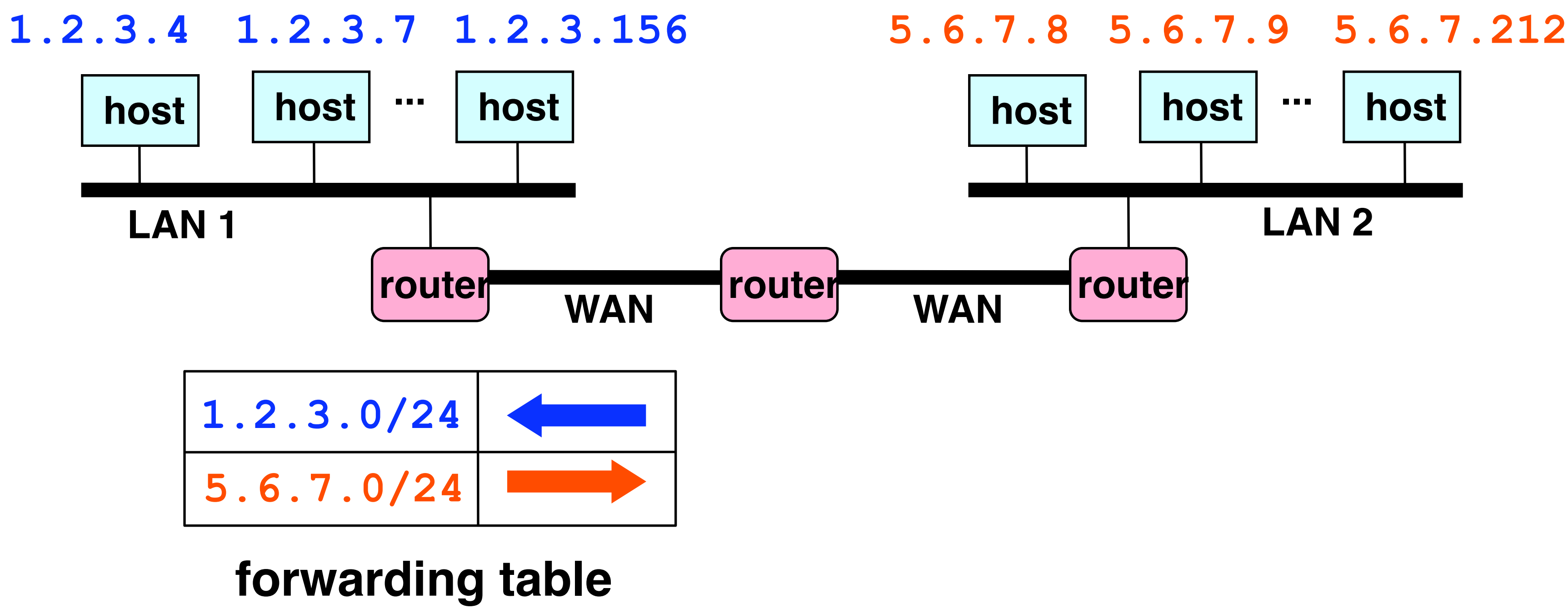
- Course was organized around protocols
  - But a small set of concepts recur in many protocols
- Many of these are general CS concepts
  - Hierarchy
  - Indirection
  - Caching
  - Randomization
- Others are somewhat networking-specific
  - Soft state
  - Layering
  - (De)multiplexing
  - End-to-end argument

Hierarchy

- Scalability of large systems
  - Cannot store all information everywhere
  - Cannot centrally coordinate each component
- Hierarchy as a way to manage scale
  - Divide large system into smaller pieces
  - And manage the pieces separately
- Hierarchy as a way to divide control
  - Decentralized management of common infrastructure
- Examples of hierarchy in the Internet
  - Example #1: IP address blocks
  - Example #2: routing protocols
  - Example #3: Domain Name System (DNS)
  - Example #4: super-peers in P2P systems

Hierarchy: IP Address Blocks

- Number related hosts from a common subnet
  - 1.2.3.0/24 on the left LAN
  - 5.6.7.0/24 on the right LAN

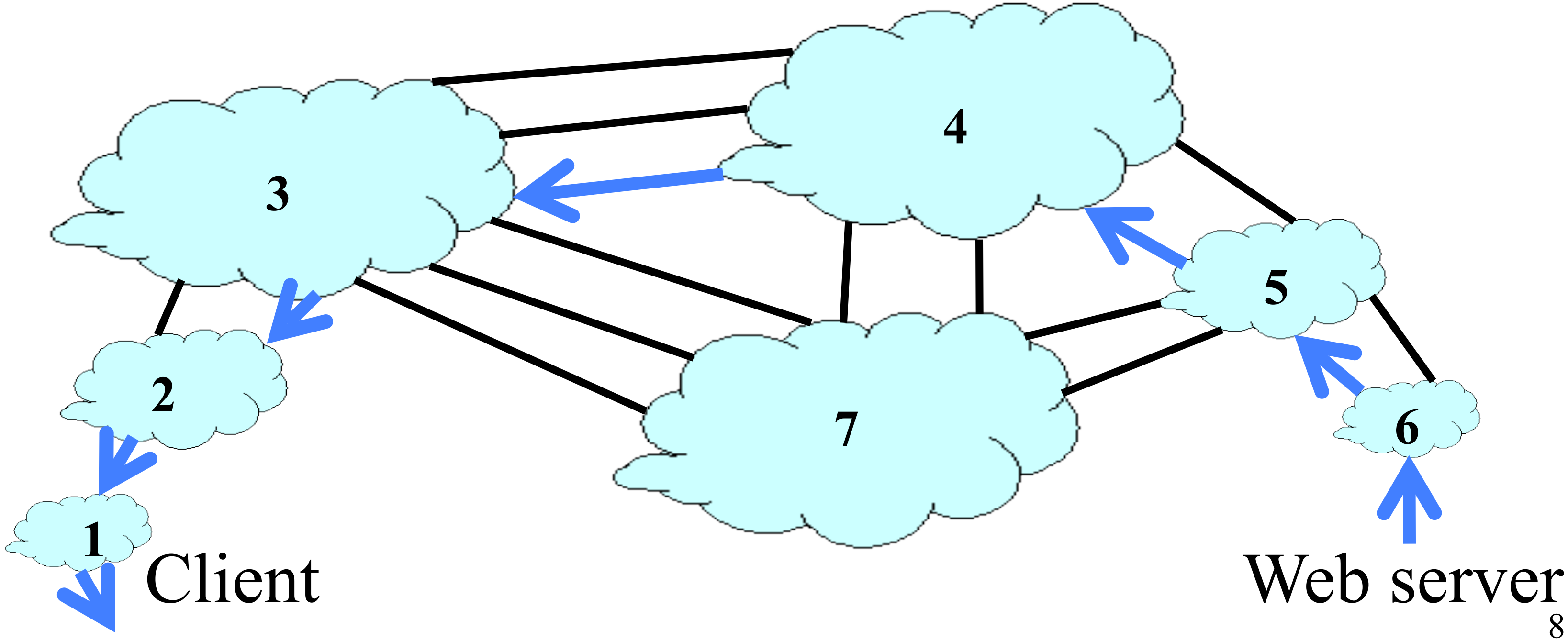


Hierarchy: IP Address Blocks

- Separation of control
  - Prefix: assigned *to* an institution
  - Addresses: assigned *by* the institution to their nodes
- Who assigns prefixes?
  - Internet Corporation for Assigned Names and Numbers
    - Allocates large address blocks to Regional Internet Registries
  - Regional Internet Registries (RIRs)
    - E.g., ARIN (American Registry for Internet Numbers)
    - Allocates address blocks within their regions
    - Allocated to Internet Service Providers and large institutions
  - Internet Service Providers (ISPs)
    - Allocate address blocks to their customers
    - Who may, in turn, allocate to their customers…

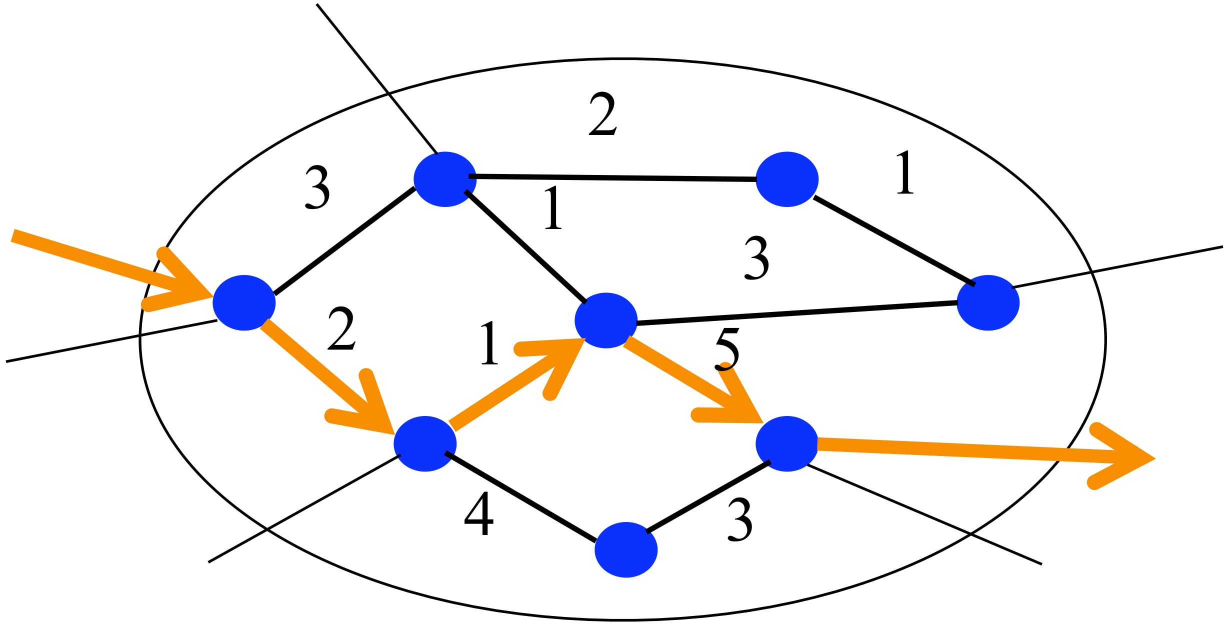
Hierarchy: Routing Protocols

- AS-level topology
  - Nodes are Autonomous Systems (ASes)
  - Edges are links and business relationships
  - Hides the detail within each AS's network



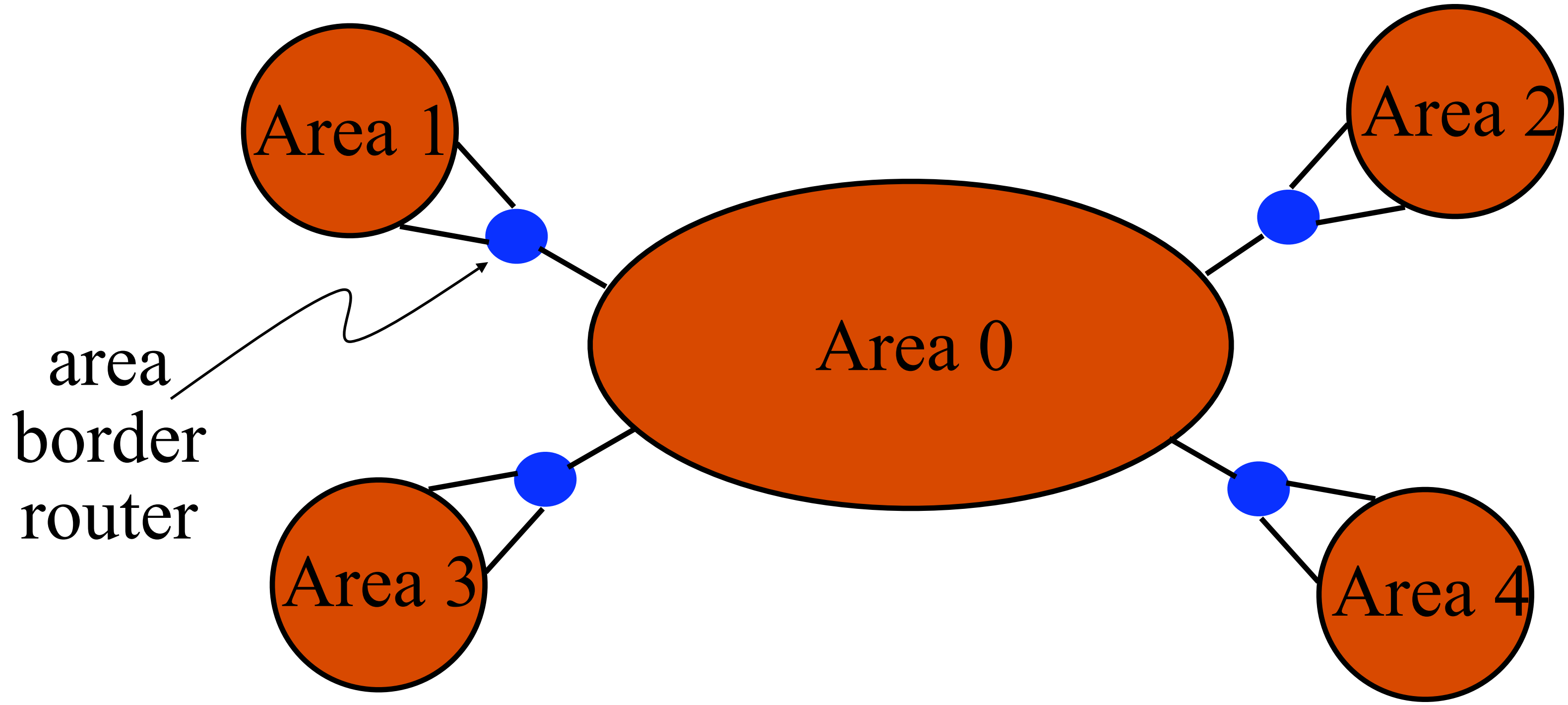
Hierarchy: Routing Protocols

- Interdomain routing ignores details within an AS
  - Routers flood information to learn the topology
  - Routers determine "next hop" to reach other routers…
  - By computing shortest paths based on the link weights



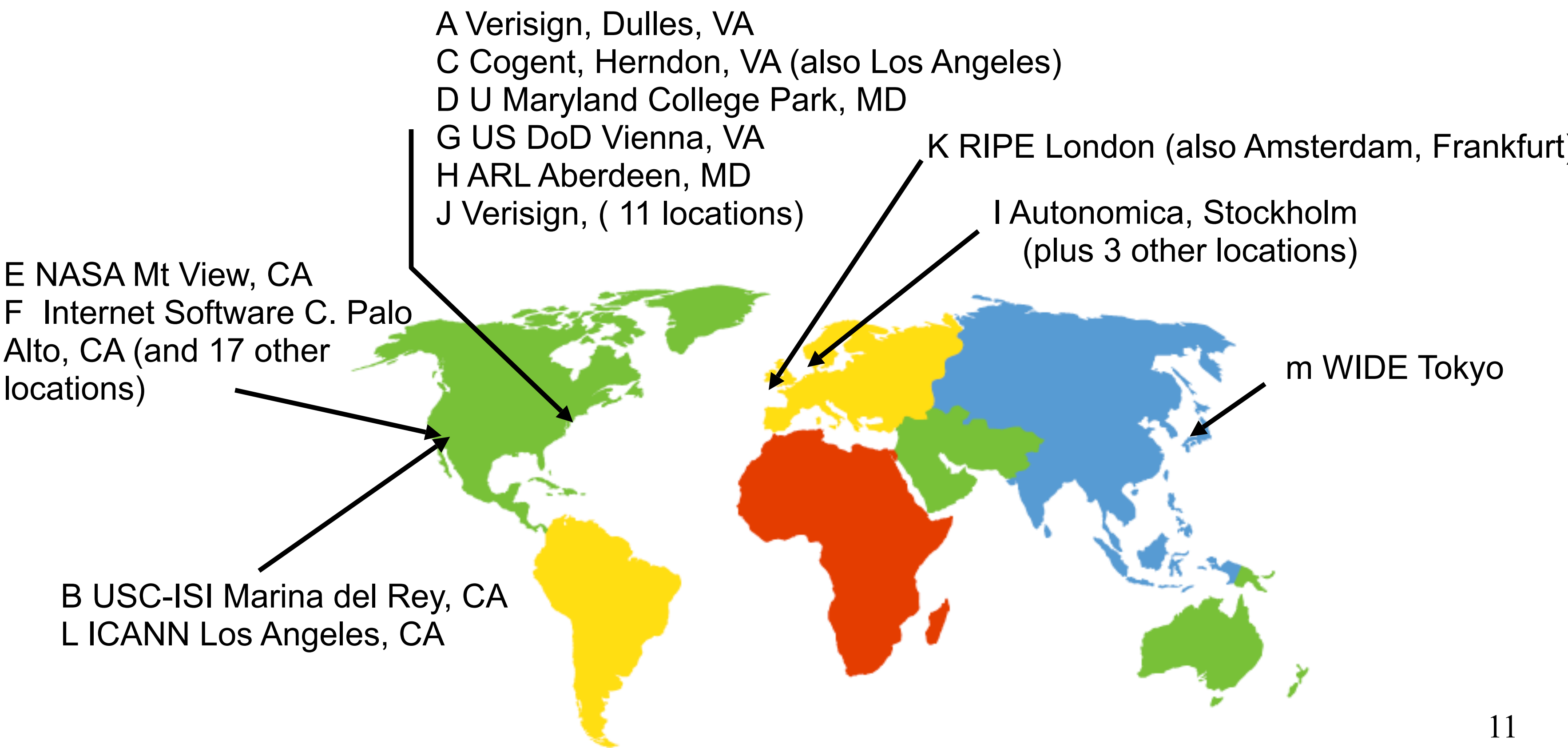
Hierarchy: Routing Protocols

- Scaling challenges within an AS
  - Flooding link-state packets throughout the network
  - Running Dijkstra's shortest-path algorithm
- Introduce hierarchy through "areas"

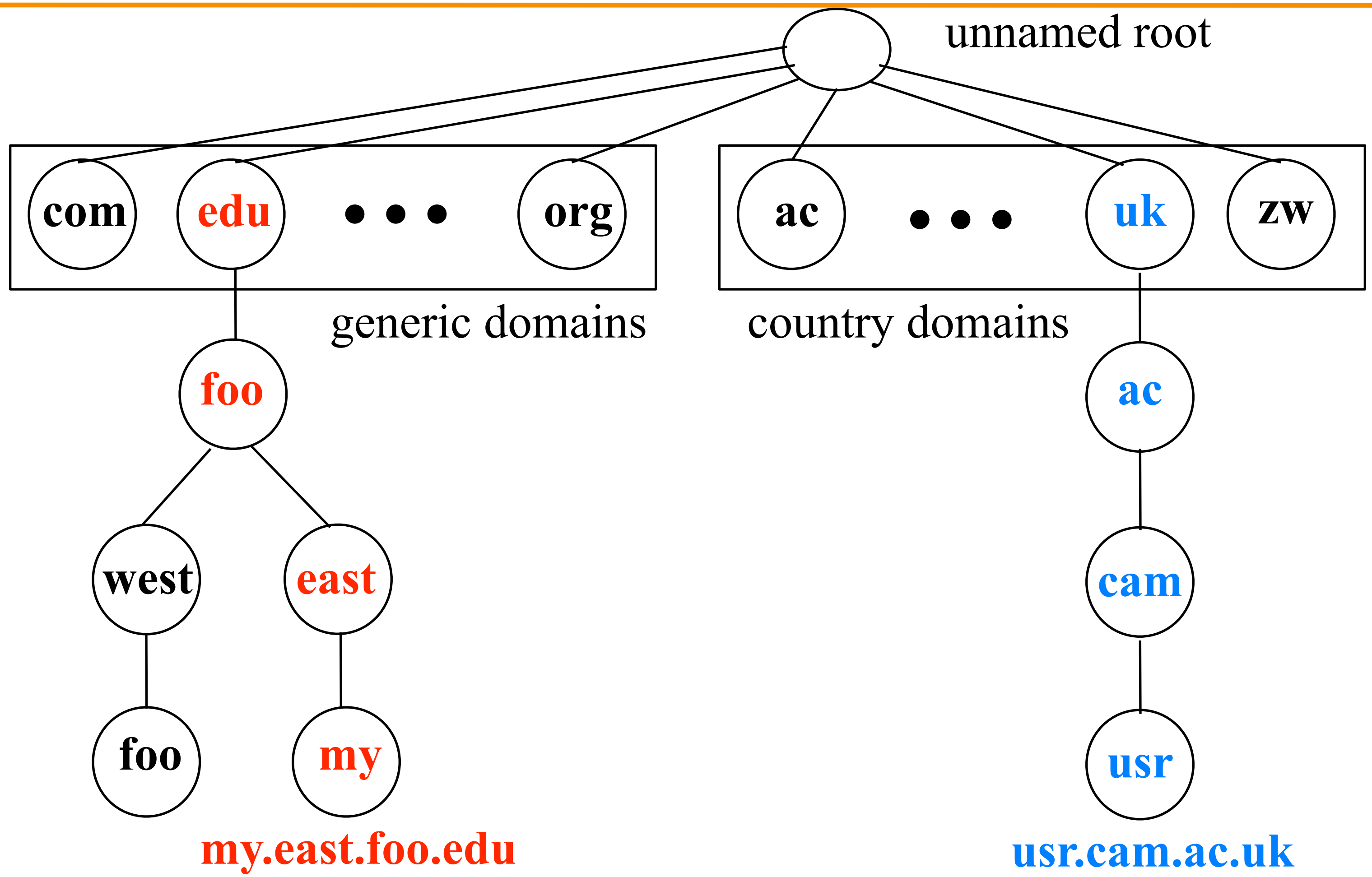


Hierarchy: Domain Name System

- 13 root servers (see http://www.root-servers.org/)
- Labeled A through M

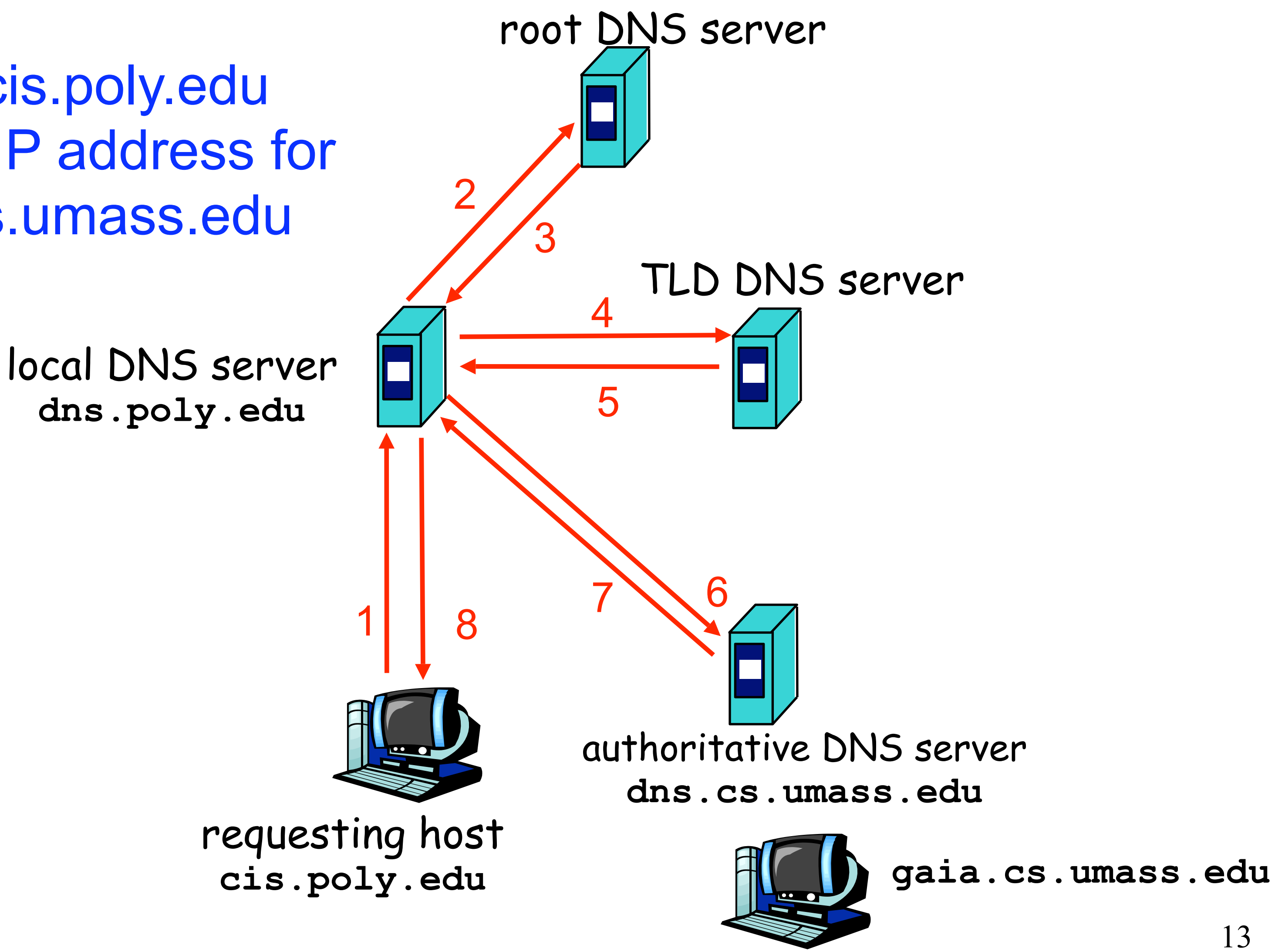


Hierarchy: Domain Name System



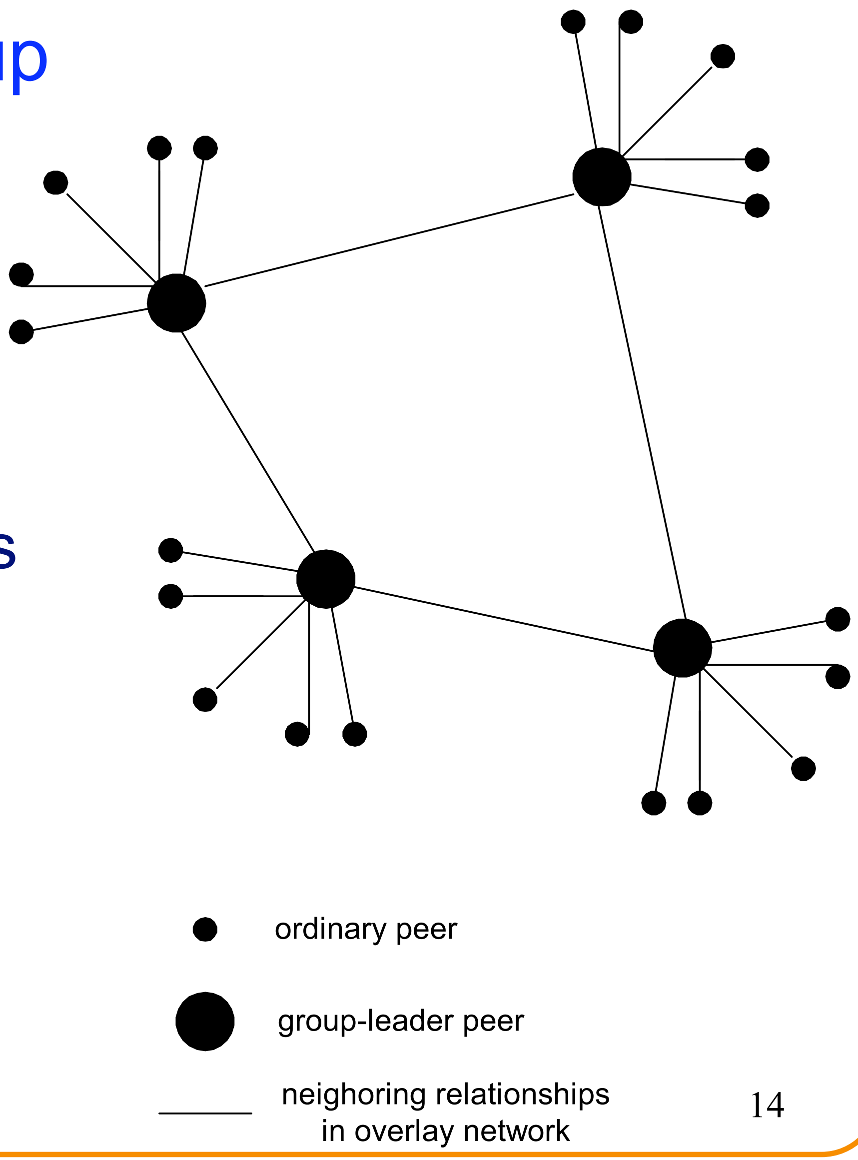
Hierarchy: Domain Name System

Host at cis.poly.edu wants IP address for gaia.cs.umass.edu



Hierarchy: Super Peers in KaZaA

- Each peer is either a group leader or assigned to a group leader
  - TCP connection between peer and its group leader
  - TCP connections between some pairs of group leaders
- Group leader tracks the content in all its children



Indirection

- Referencing by name
  - Rather than the value itself
  - E.g., manipulating a variable through a pointer
- Benefits of indirection
  - Human convenience
  - Reducing overhead when things change
- Examples of indirection in the Internet
  - Example #1: host names instead of IP addresses
  - Example #2: mobile IP

Indirection: Host Names vs. Addresses

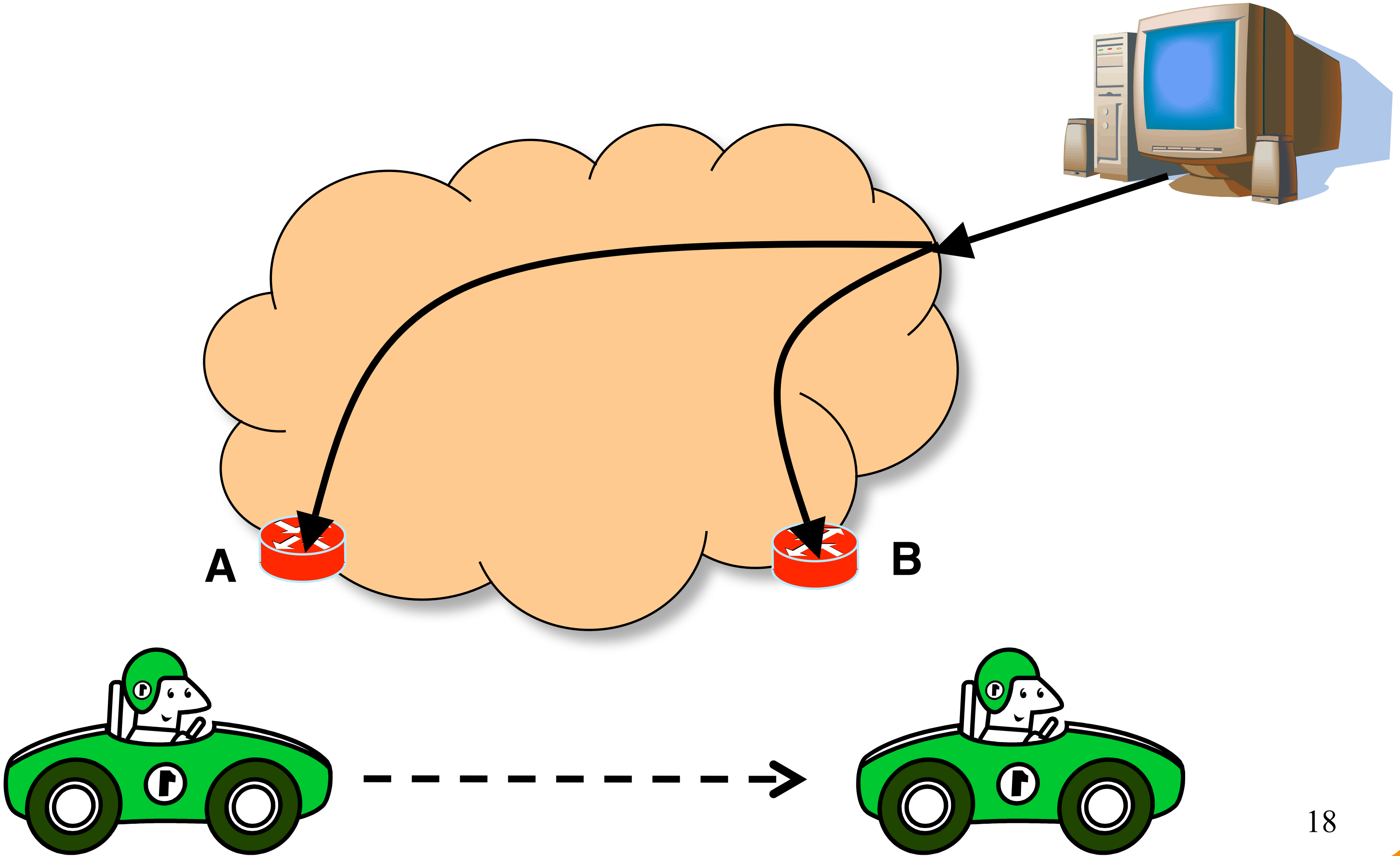
- Host names
  - Mnemonic name appreciated by humans
  - Variable length, alpha-numeric characters
  - Provide little (if any) information about location
  - Examples: www.cnn.com and ftp.eurocom.fr
- IP addresses
  - Numerical address appreciated by routers
  - Fixed length, binary number
  - Hierarchical, related to host location
  - Examples: 64.236.16.20 and 193.30.227.161

Indirection: Host Names vs. Addresses

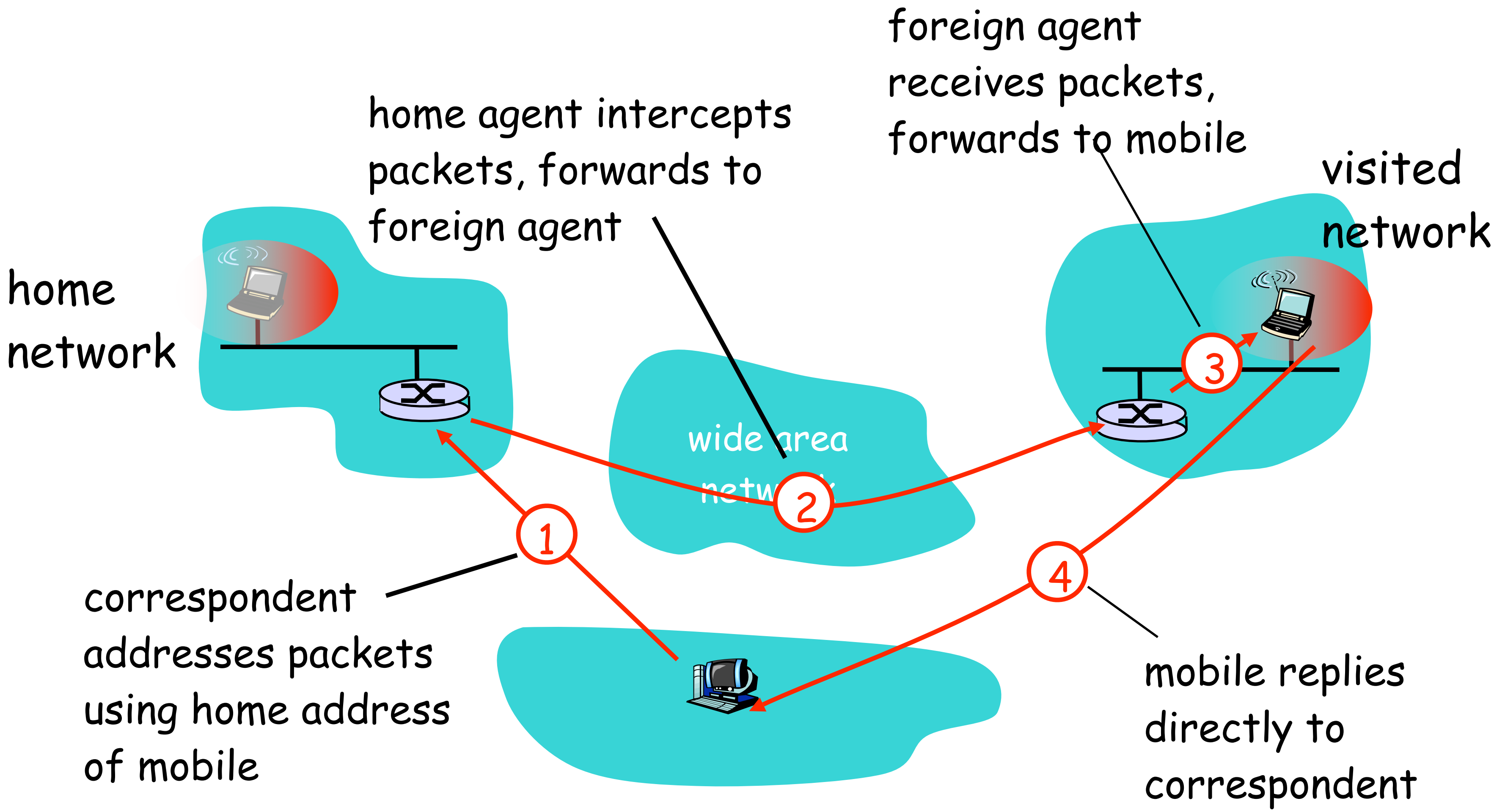
- Names are easier to remember
  - www.cnn.com vs. 64.236.16.20
- Addresses can change underneath
  - Move www.cnn.com to 173.15.201.39
  - E.g., renumbering when changing providers
- Name could map to multiple IP addresses
  - www.cnn.com to multiple replicas of the Web site
- Map to different addresses in different places
  - Address of a nearby copy of the Web site
  - E.g., to reduce latency, or return different content
- Multiple names for the same address
  - E.g., aliases like ee.mit.edu and cs.mit.edu

Indirection: Mobile IP

- Seamless transmission to a mobile host



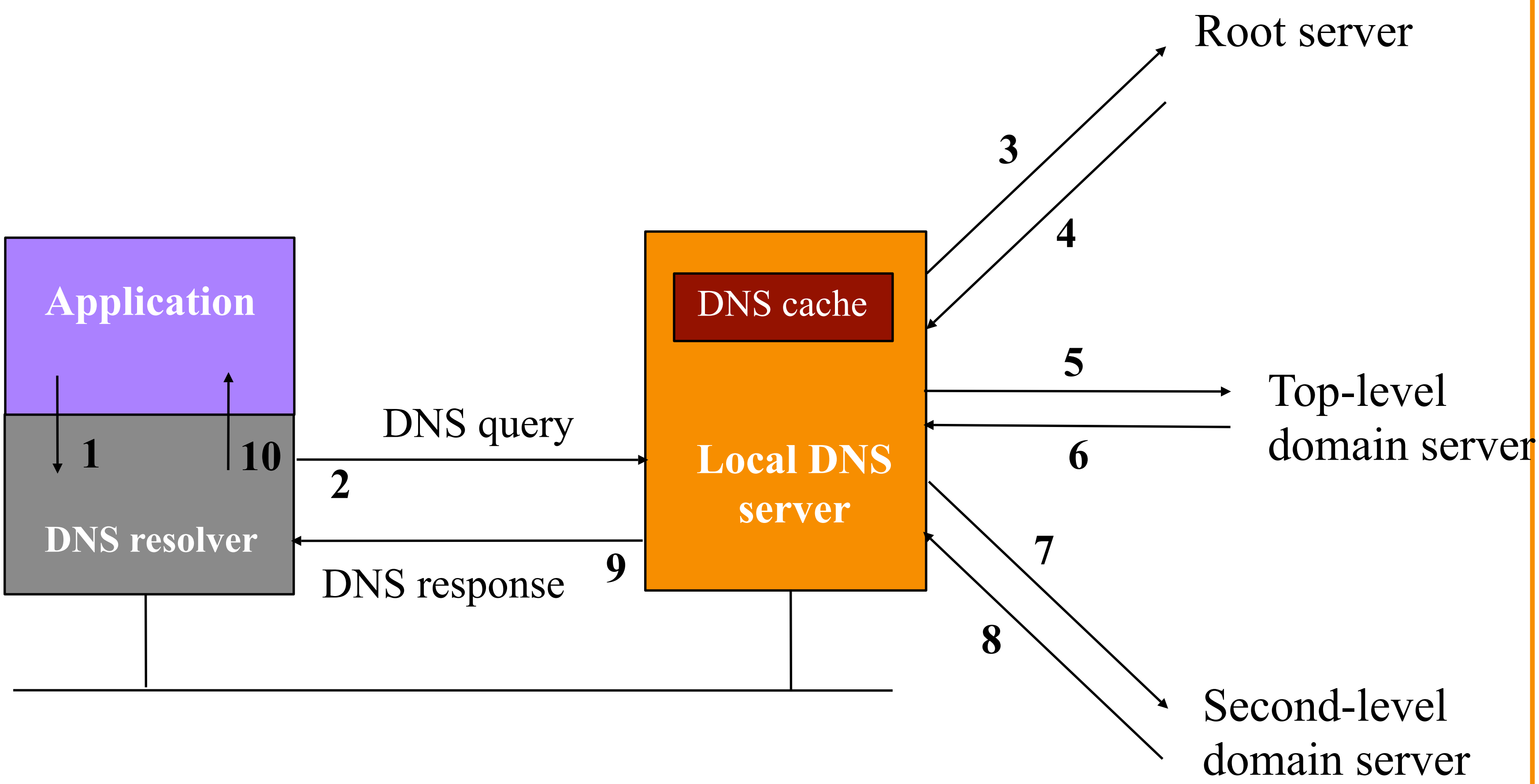
Indirection: Mobile IP



Caching

- Duplicating data stored elsewhere
  - To reduce latency for accessing the data
  - To reduce resources consumed
- Caching is often quite effective
  - Speed difference between cache and primary copy
  - Locality of reference, and small set of popular data
- Examples from the Internet
  - Example #1: DNS caching
  - Example #2: Web caching

Caching: DNS Caching



Caching: DNS Caching

- What is cached?
  - Mapping of names to IP addresses
  - IP addresses for DNS servers (e.g., for .com)
  - DNS queries that failed (e.g., www.cnn.comm)
- Why it reduces latency?
  - DNS queries can take a long time (e.g., 1 second)
  - Local DNS server is typically very close to the users
- Why is the cache hit rate is very high?
  - Cached information remains valid for awhile
  - Popular sites (e.g., www.cnn.com) are visited often
  - The cache is shared among a group of users

Caching: Web Caching

- What is cached?
  - Web object, like an HTML file or embedded image
- Where is it cached?
  - Browser cache, proxy cache, main-memory on server
- Why it reduces latency?
  - Avoids fetching across the network (or the disk)
  - Reduces load on the network and the server
- What helps increase the hit rate?
  - Cacheable content (not dynamically generated)
  - Sharing of the cache among multiple users
  - Small amount of very popular content

Randomization

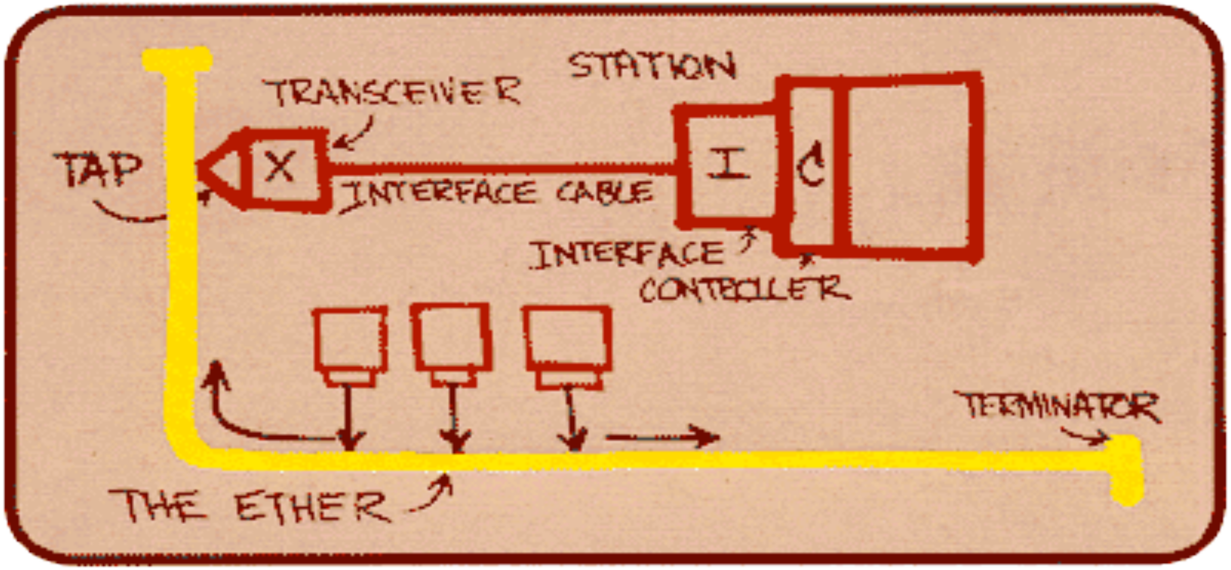
- Distributed adaptive algorithms
  - Multiple distributed parties
  - Adapting to network conditions independently
- Risk of synchronization
  - Many parties reacting at the same time
  - Leading to bad aggregate behavior
- Randomization can desynchronize
  - Example #1: Ethernet back-off mechanism
  - Example #2: Random Early Detection
- Rather than imposing centralized control

Randomization: Ways to Share Media

- Channel partitioning MAC protocols:
  - Share channel efficiently and fairly at high load
  - Inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!
- "Taking turns" protocols
  - Eliminates empty slots without causing collisions
  - Vulnerable to failures (e.g., failed node or lost token)
- Random access MAC protocols
  - Efficient at low load: single node can fully utilize channel
  - High load: collision overhead

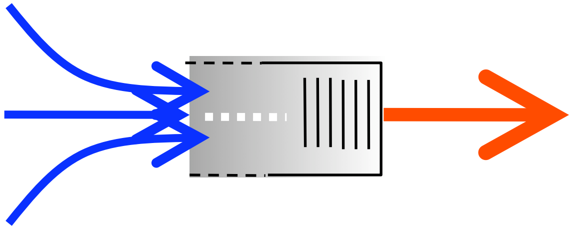
Randomization: Ethernet Back-off

- Random access: exponential back-off
  - After collision, wait random time before retrying
  - After m^{th}, choose K randomly from $\{0, \ldots, 2^m-1\}$
  - Wait for K*512 bit times before trying again



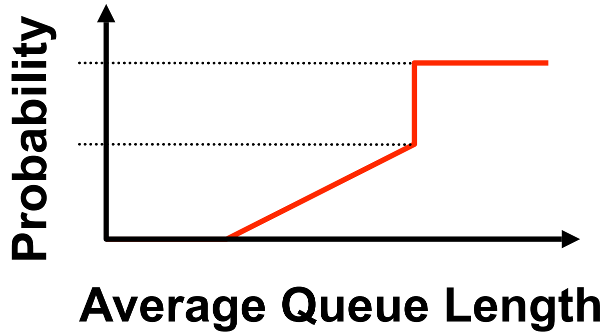
Randomization: Dropping Packets Early

- Congestion on a link
  - Eventually the queue becomes full
  - And new packets must be dropped
- Drop-tail queuing leads to *bursty* loss
  - Many packets encounter a full queue
  - Many TCP senders reduce their sending rates



Randomization: Dropping Packets Early

- Better to give early feedback
  - Get a few connections to slow down
  - … before it is too late
- Random Early Detection (RED)
  - Randomly drop packets when queue (near) full
  - Drop rate increases as function of queue length



Networking Has Some Key Concepts

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  - But a small set of concepts recur in many protocols
- Many of these are general CS concepts
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- Others are somewhat networking-specific
  - Soft state
  - Layering
  - (De)multiplexing
  - End-to-end argument

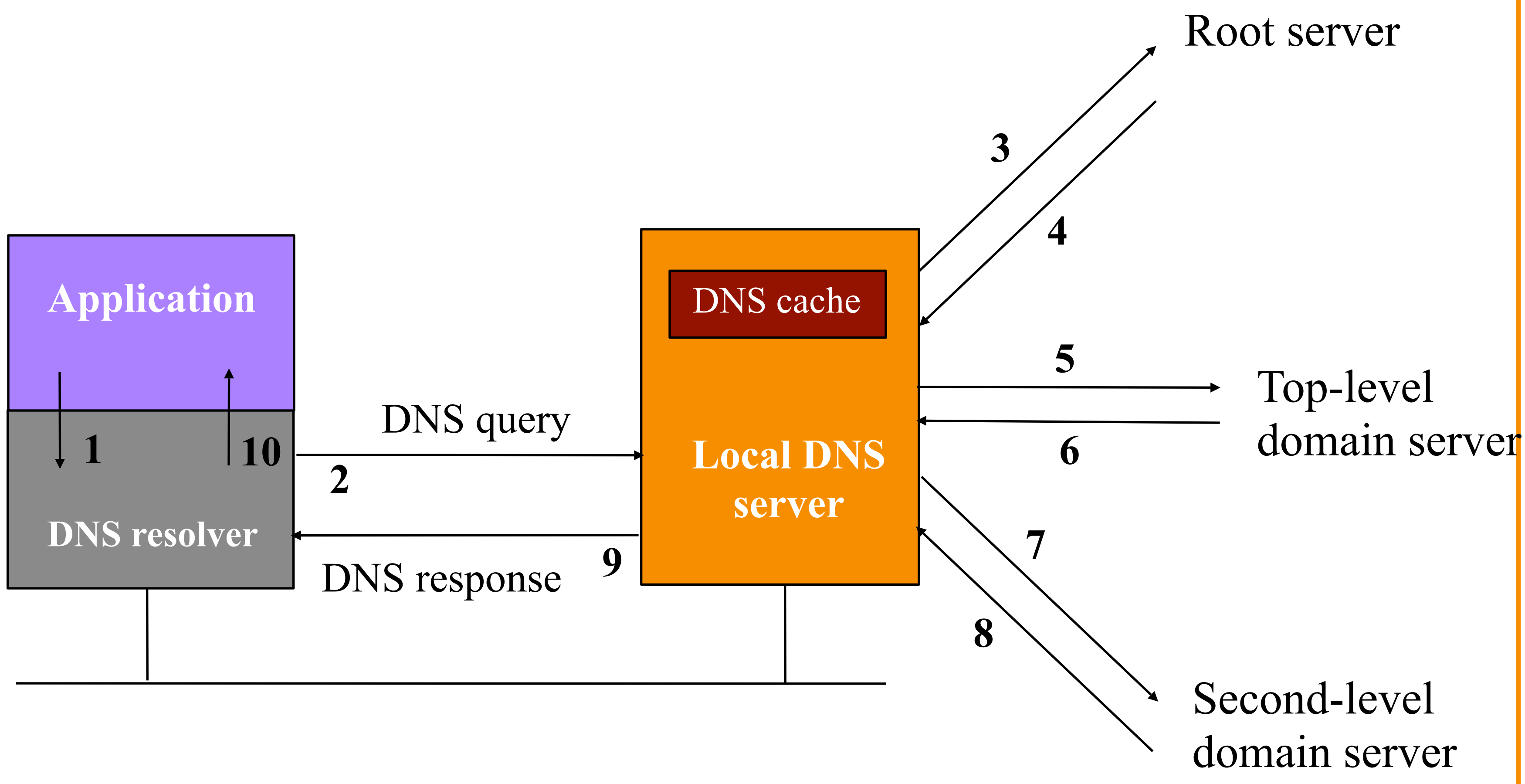
Soft State

- State: stored in nodes by network protocols
  - Installed by receiver of a set-up message
  - Updated when network conditions change
- Hard state: valid unless told otherwise
  - Removed by receiver of a tear-down message
  - Requires error handling to deal with sender failure

- Soft state: invalid if not told to refresh
  - Removed by receiver via a timeout
  - Periodically refreshed as needed

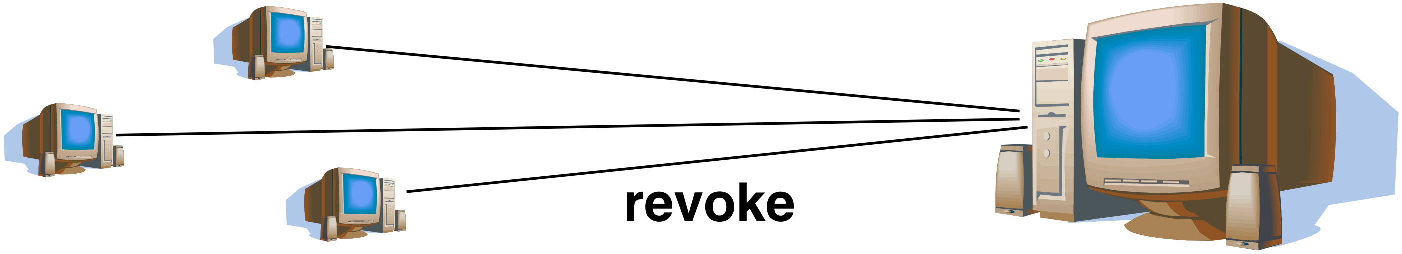
- Soft state reduces complexity
  - Example #1: DNS caching
  - Example #2: DHCP leases

Soft State: DNS Caching

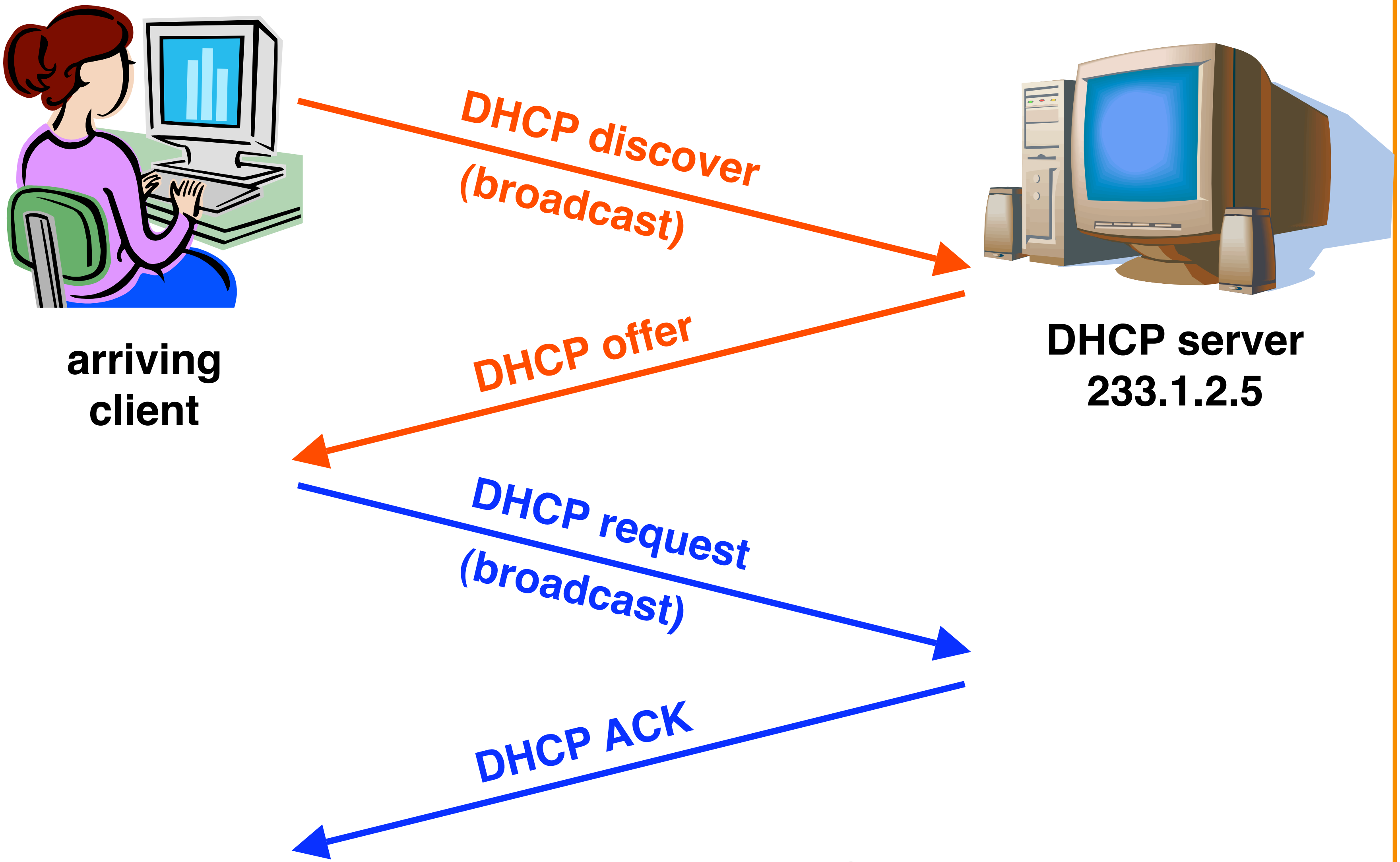


Soft State: DNS Caching

- Cache consistency is a hard problem
  - Ensuring the cached copy is not out of date
- Strawman: explicit revocation or updates
  - Keep track of everyone who has cached information
  - If name-to-host mapping changes, update the caches
  - If you fail to reach a cache, keep trying till success
- Soft state solution
  - DNS responses include a “time to live” (TTL) field
  - Cached entry is deleted after TTL expires



Soft State: DHCP Bootstrapping



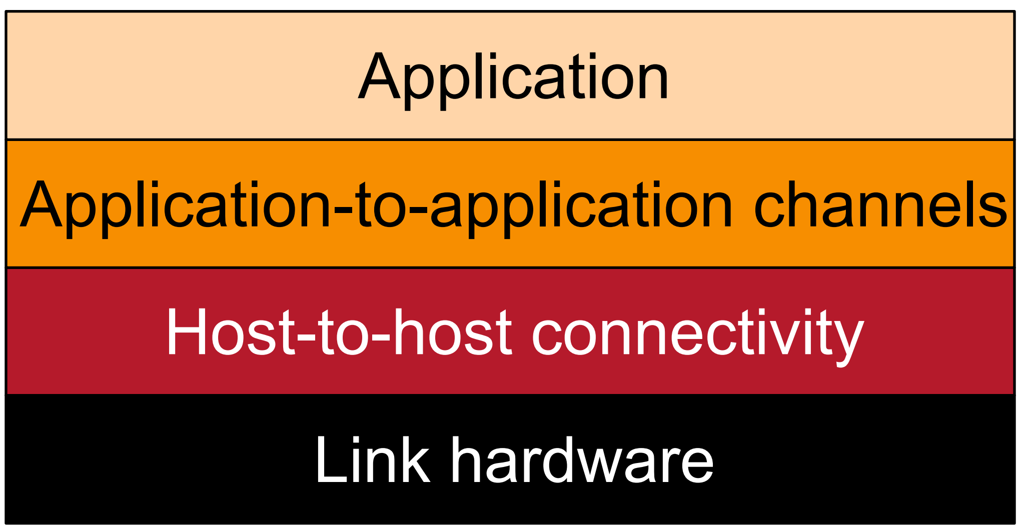
Dynamic Host Configuration Protocol

Soft State: DHCP Leases

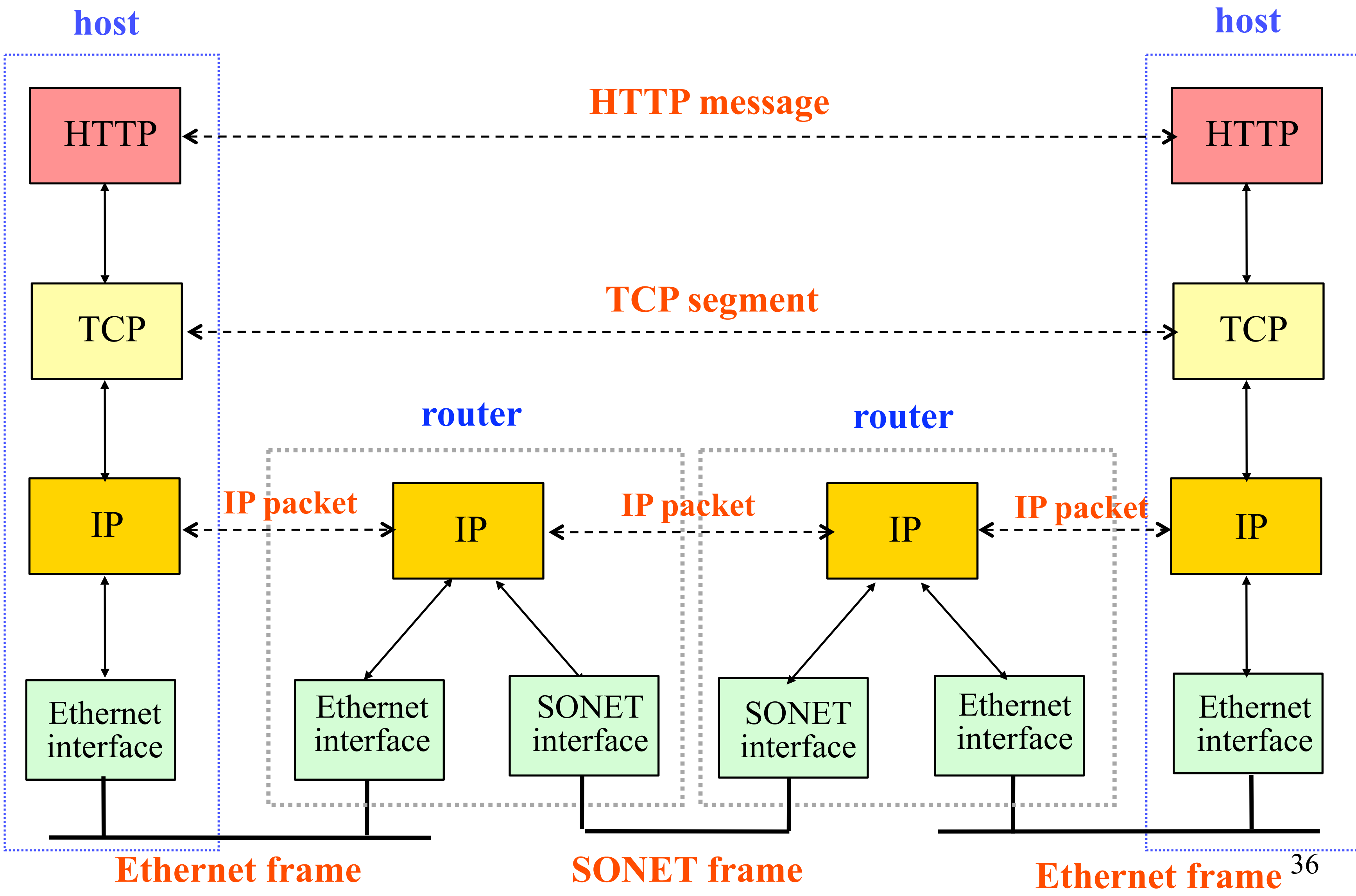
- DHCP "offer message" from the server
  - Configuration parameters (proposed IP address, mask, gateway router, DNS server, ...)
  - Lease time (the time information remains valid)
- Why is a lease time necessary?
  - Client can release address (DHCP RELEASE)
    - E.g., "ipconfig /release" at the DOS prompt
    - E.g., clean shutdown of the computer
  - But, the host might *not* release the address
    - E.g., the host crashes (blue screen of death!)
    - E.g., buggy client software
  - You don't want address to be allocated forever

Layering: A Modular Approach

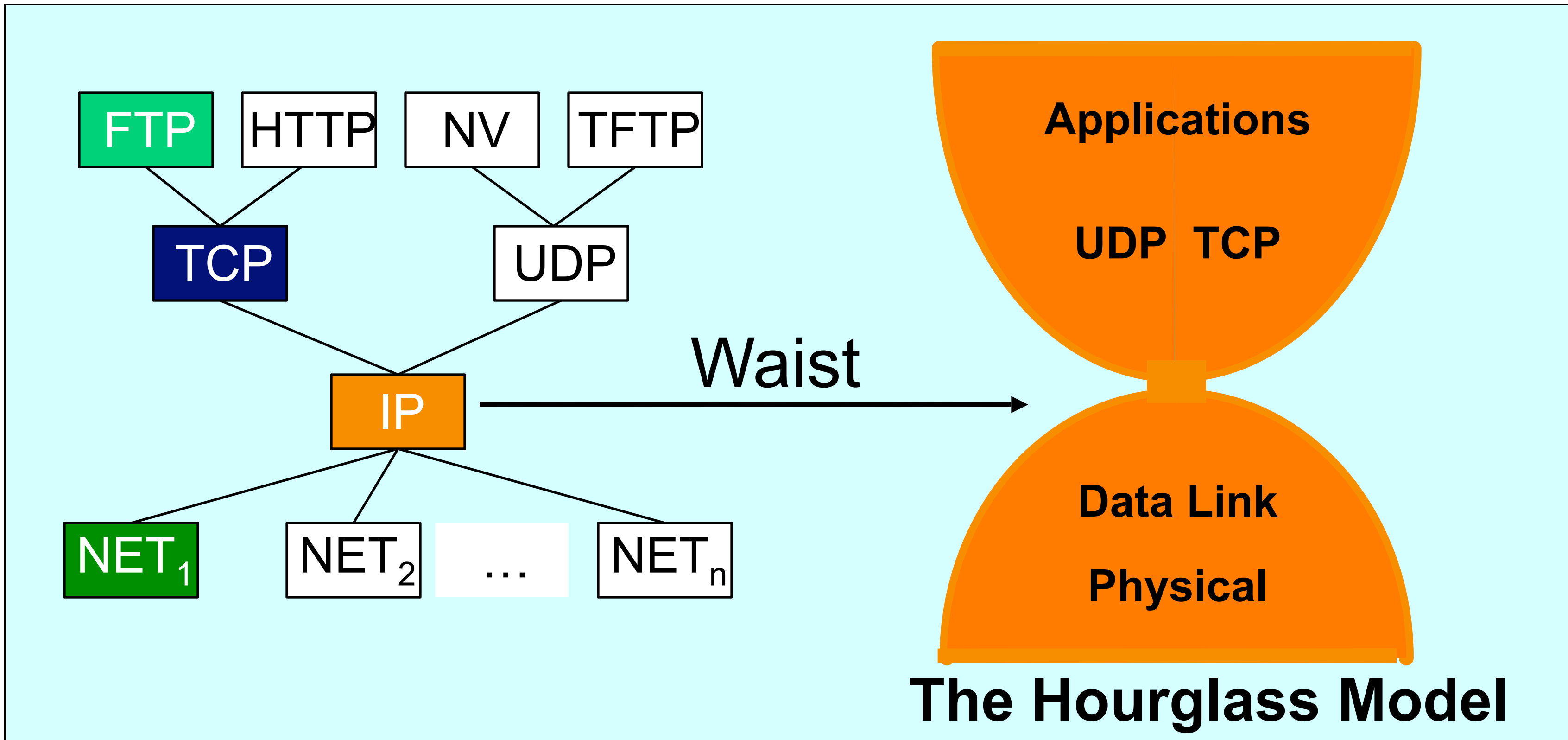
- Sub-divide the problem
  - Each layer relies on services from layer below
  - Each layer exports services to layer above
- Interface between layers defines interaction
  - Hides implementation details
  - Layers can change without disturbing other layers



Layering: Standing on Shoulders



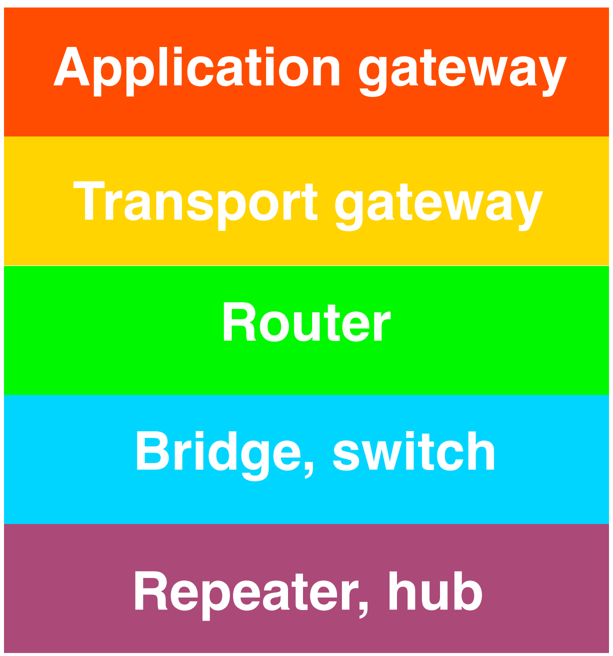
Layering: Internet Protocol Suite

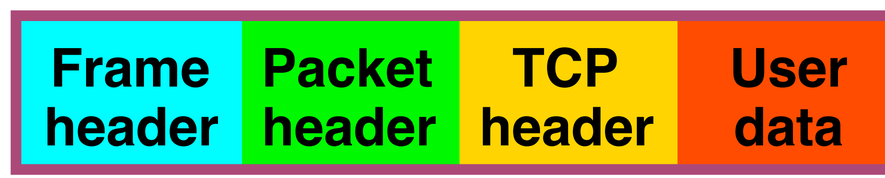


The waist facilitates interoperability

Layering: Encapsulation of Data

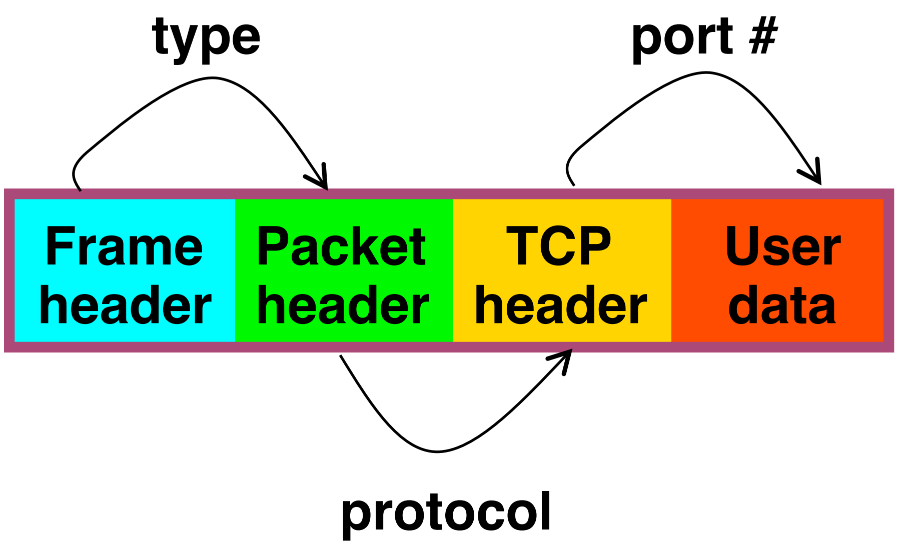
- Different devices switch different things
  - Physical layer: electrical signals (repeaters and hubs)
  - Link layer: frames (bridges and switches)
  - Network layer: packets (routers)



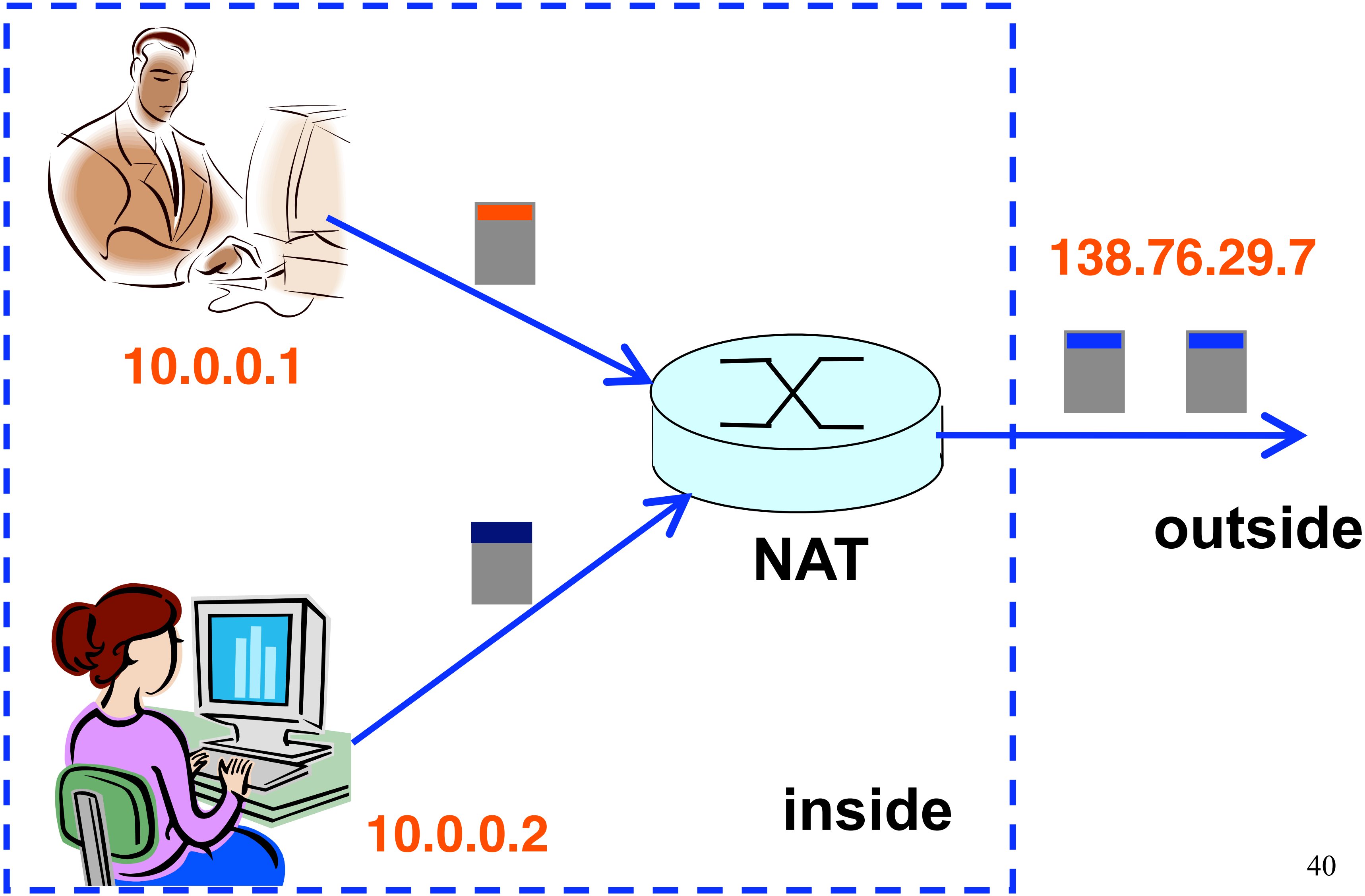


Demultiplexing

- Separating multiple streams out of one
  - Recognizing the separate streams
  - Treating the separate streams accordingly
- Examples in the Internet



(De)multiplexing: With a NAT



Power at the End Host

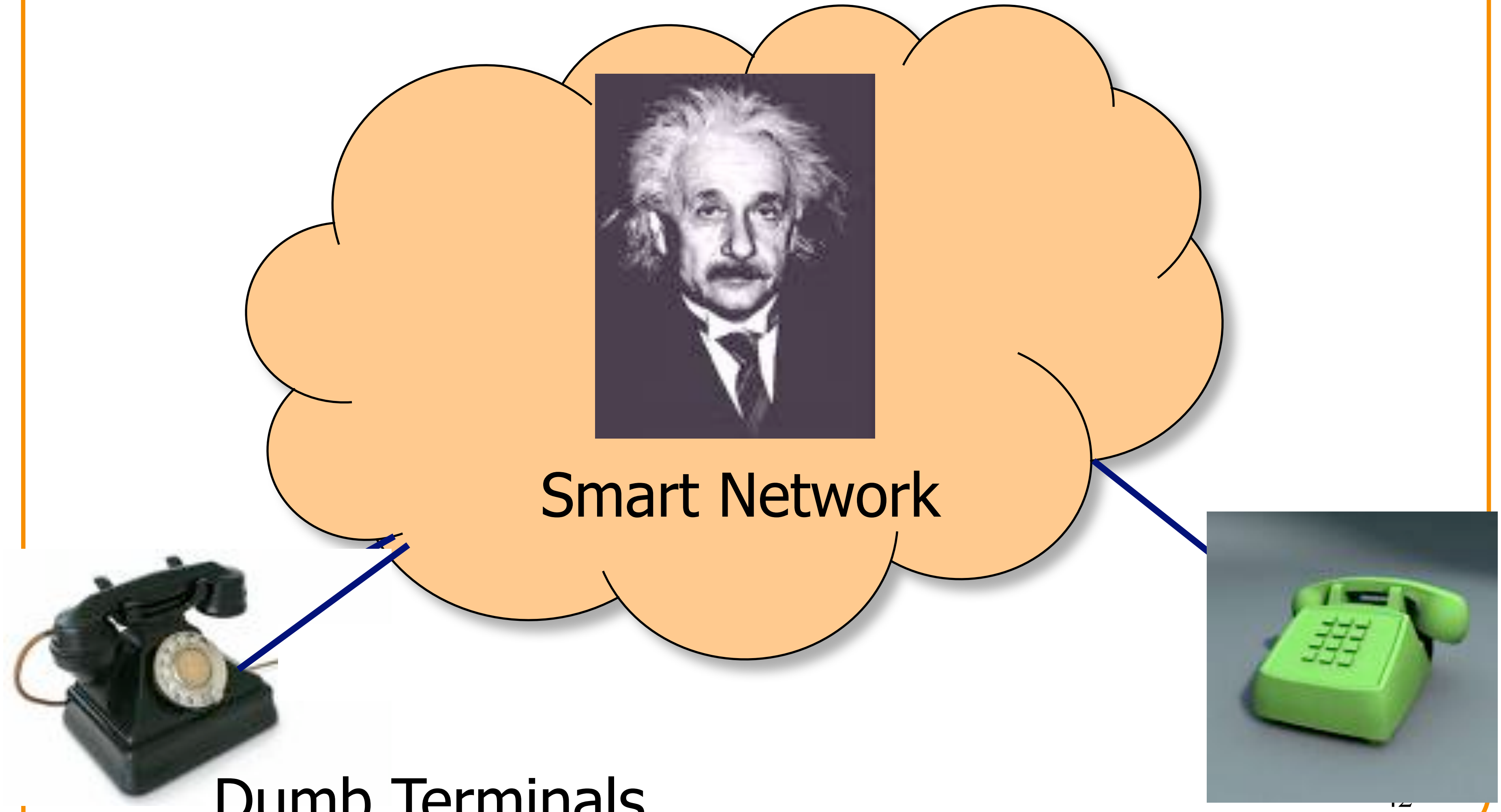
End-to-End Principle

Whenever possible, communications protocol operations should be defined to occur at the end-points of a communications system.

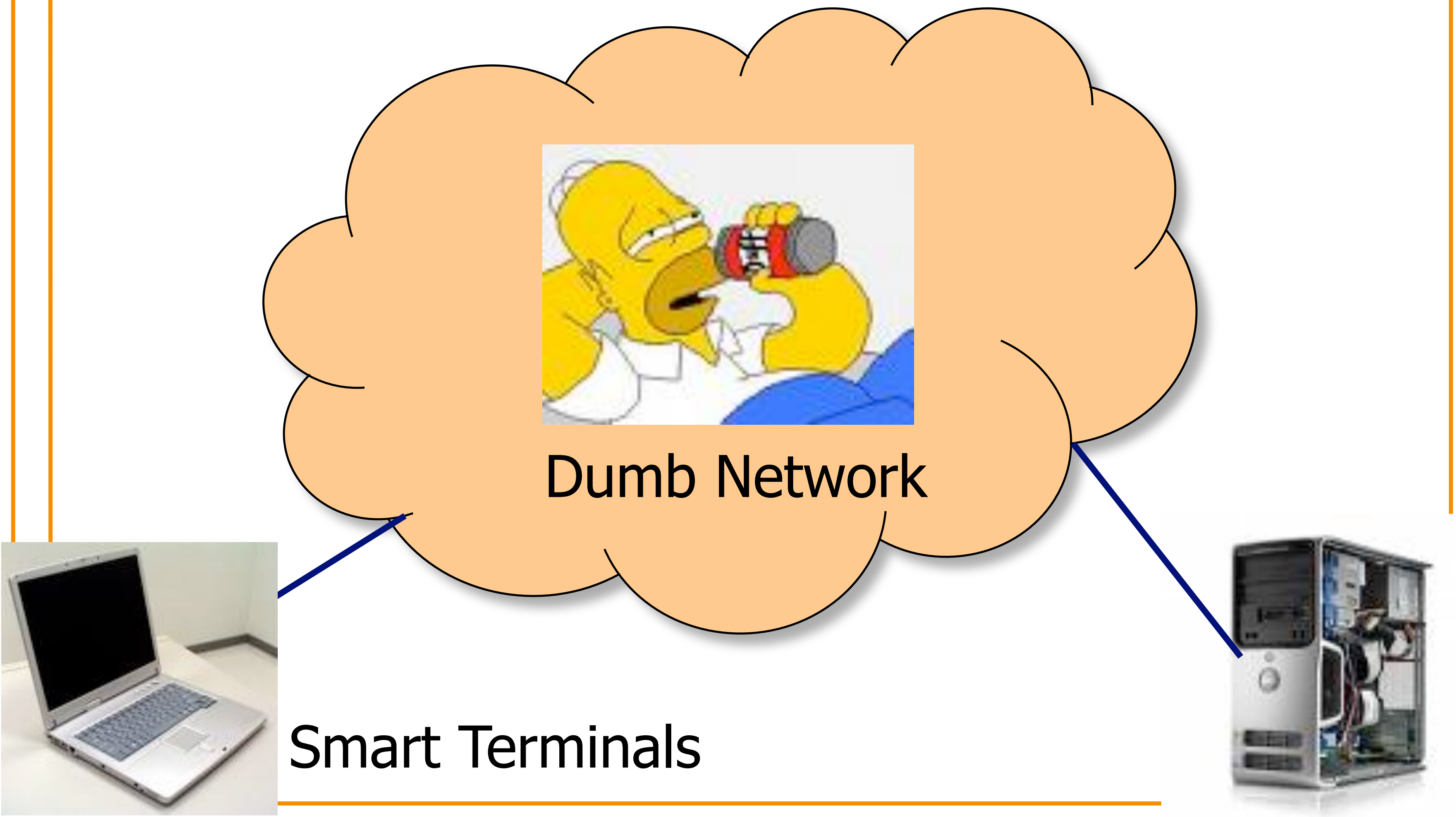
Programmability

With programmable end hosts, new network services can be added at any time, by anyone.

Telephone Network



Internet



Why No Math in This Course?

- Hypothesis #1: theory not relevant to the Internet
  - Body of mathematics created for telephone networks
  - Teletraffic modeling, computing call blocking statistics
  - Many of these models don’t work in data networks
- Hypothesis #2: too many kinds of math to cover
  - Queuing theory: statistical multiplexing works
  - Control theory: TCP congestion control works
  - Optimization theory: TCP maximizes aggregate utility
  - Game theory: reasoning about competing ASes
  - We still need to build a much stronger foundation…

What Will Happen to the Internet

No Strict Notions of Identity

"On the Internet, nobody knows you're a dog."

- Leads to
  - Spam
  - Spoofing
  - Denial-of-service
  - Route hijacking

Protocols Designed Based on Trust

- That you don't spoof your addresses
  - MAC spoofing, IP address spoofing, spam, …
- That port numbers correspond to applications
  - Rather than being arbitrary, meaningless numbers
- That you adhere to the protocol
  - Ethernet exponential back-off after a collision
  - TCP additive increase, multiplicative decrease
- That protocol specifications are public
  - So others can build interoperable implementations

Nobody in Charge

- Traffic traverses many Autonomous Systems
  - Who's fault is it when things go wrong?
  - How do you upgrade functionality?
- Implicit trust in the end host
  - What if some hosts violate congestion control?
- Anyone can add any application
  - Whether or not it is legal, moral, good, etc.
- Nobody knows how big the Internet is
  - No global registry of the topology
- Spans many countries
  - So no government can be in charge

Challenging New Requirements

- Disseminating data
  - Rather than communicating between two machines
- Mobile hosts
  - Rather than machines at a fixed location
- Sometimes-connected hosts
  - Developing regions with intermittent connectivity
- Large number of hosts
  - Billions of small networked devices (e.g., sensors)
- Real-time applications
  - Voice over IP, gaming, and IPTV

The Internet of the Future

- Can we fix what ails the Internet
  - Security
  - Performance
  - Upgradability
  - Managability
  - <your favorite gripe here>
- Without eliminating the good things
  - Ease of adding new hosts
  - Ease of adding new services
  - Ease of adding new link technologies
- An open technical and policy question…

Thank You!