COS 561: Advanced Computer Networks

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http://www.cs.princeton.edu/courses/archive/fall26/cos561/

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The Internet: (Still) An Exciting Time

- One of the most influential inventions
  - A research experiment that escaped from the lab
  - … to be a global communications infrastructure
- Ever wider reach
  - Today: more than 3 billion users
  - Tomorrow: more users, computers, things, …
- Near-constant innovation
  - Apps: Web, P2P, social networks, virtual reality
  - Links: optics, Wi-Fi, cellular, Satellite, ...

Transforming Everything

- The ways we do business
  - E-commerce, advertising, cloud computing, ...
- The way we have relationships
- How we think about law
  - Interstate commerce? National boundaries?
- The way we govern
  - E-voting and e-government
  - Censorship and wiretapping
- The way we fight
  - Cyber-attacks, including nation-state attacks

Networking is Cool

- Tangible, relates to reality
  - Can measure and build things
  - Can truly effect far-reaching change in the real world
- Inherently interdisciplinary
  - Well-motivated problems + rigorous solution techniques
  - Interplay with policy, economics, and social science
- Widely-read papers
  - Many of the most cited papers in CS are in networking
  - Congestion control, distributed hash tables, resource reservation, self-similar traffic, multimedia protocols,…

Networking is Cool

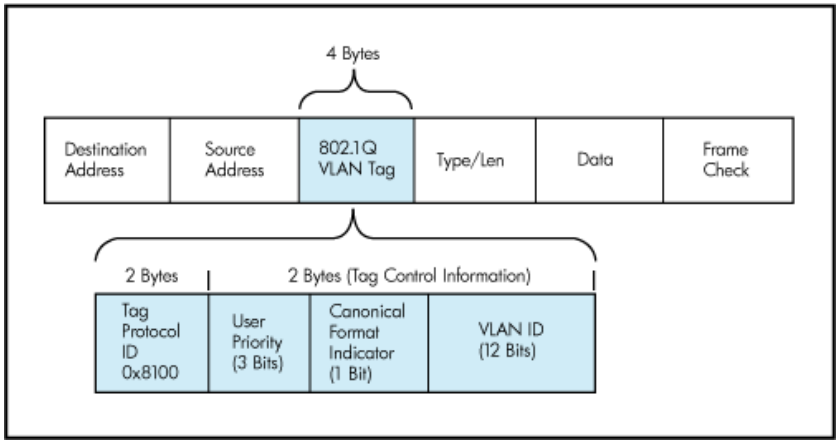
- ~~Young~~, relatively immature field
  - Great if you like to make order out of chaos
  - Tremendous intellectual progress is still needed
  - *You* can help decide what networking really is
- Defining the problem is a big part of the challenge
  - Recognizing a need, formulating a well-defined problem
  - … is at least as important as solving the problem…
- Lots of platforms for building your ideas
  - Programmability: Click, OpenFlow, NetFPGA, P4, Lucid
  - Testbeds: PlanetLab, Orbit, PAWR, …
  - Measurements: RouteViews, traceroute, Internet2, …

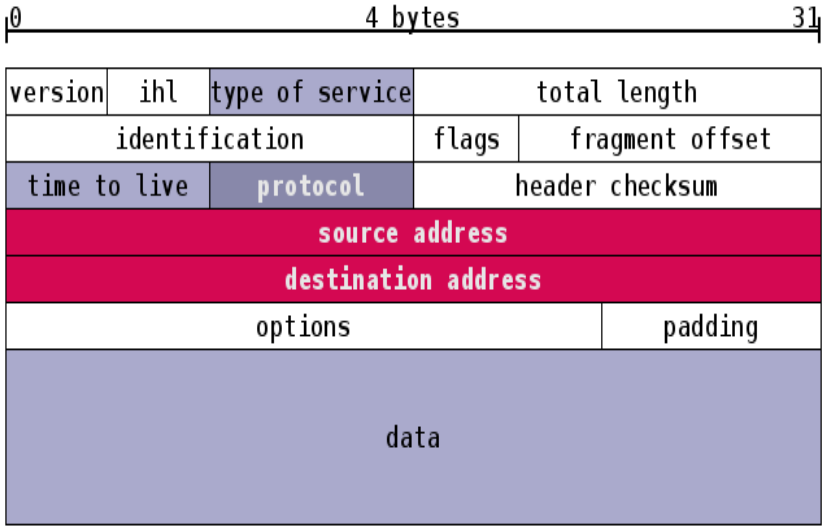
But, What *is* Networking?

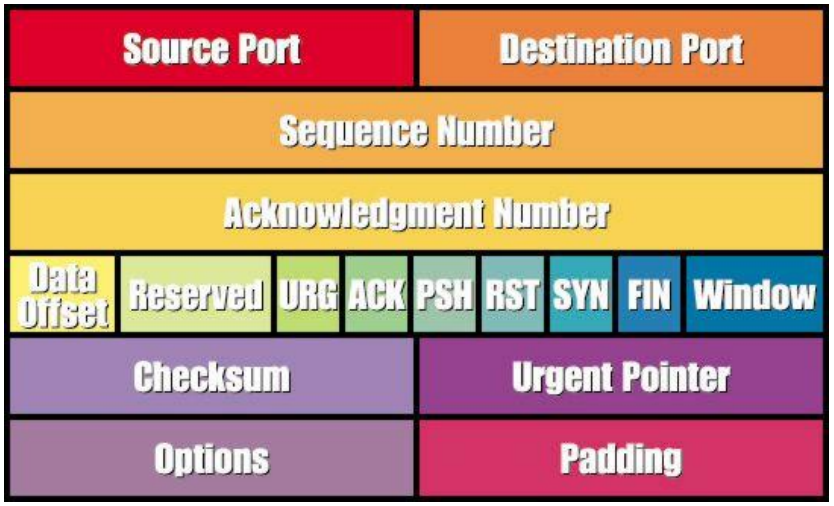
A Plethora of Protocol Acronyms?

SNMP
WAP
SIP
IPX
PPP
MAC
LLDP
FTP
UDP
HIP
OSPF
RTP
ICMP
IMAP
IGMP
BGP
PIM
HTTP
ECN
RED
ARP
IP
RIP
TCP
MPLS
RTCP
SMTP
RTSP
BFD
CIDR
NNTP
TLS
NAT
SACK
STUN
DNS
SSH
DHCP
VTP
VLAN
POP
LISP
TFTP
LDP

A Heap of Header Formats?







HTTP Response Header

Name	Value
HTTP Status Code: HTTP/1.1 200 OK	
Date:	Thu, 27 Mar 2008 13:37:17 GMT
Server:	Apache/2.0.55 (Ubuntu) PHP/5.1.2
Last-Modified:	Fri, 21 Mar 2008 13:57:30 GMT
ETag:	"358a4e4-56000-ddf5c680"
Accept-Ranges:	bytes
Content-Length:	352256
Connection:	close
Content-Type:	application/x-msdos-program

A Big Bunch of Boxes?

Router

Label Switched Router

Load balancer

Switch

Scrubber

Repeater

Gateway

Intrusion Detection System

Bridge

Route Reflector

Deep Packet Inspection

DHCP server

Packet shaper

Firewall

NAT

Hub

Packet sniffer

WAN accelerator

DNS server

Base station

Proxy

A Ton of Tools?

arpwatch

tcpdump

syslog

wget

nslookup

traceroute

trat

snort

nmap

whois

ipconfig

rancid

ntop

bro

net-snmp

dig

ping

iperf

NDT

wireshark

dummynet

mrtg

What Do Peers in Other Fields Say?

- "You networking people are very curious. You really love your artifacts."
- "In my college networking class I fell asleep at the start of the semester when the *IP header* was on the screen, and woke up at the end of the semester with the *TCP header* on the screen."
- "Networking is all details and no principles."

Is networking "just the (arti)facts"?

What Peers in Other Fields Say?

- "Networking papers are strange. They have a lot of text."
- "What are the top ten classic problems in networking? I would like to solve one of them and submit a paper to SIGCOMM." After hearing that we don't have such a list: "Then how do you consider networking a discipline?"
- "So, these networking research people today aren't doing theory, and yet they aren't the people who brought us the Internet. What exactly are they doing?"
- "Networking is an opportunistic discipline."

Is networking a problem domain or a scholarly discipline?

But, That Doesn't Say What Networking Really *Is*

Or, What Will This Course Be About?

One Take on Defining Networking

- How to
  - Design and manage *protocols*
  - That can be used and *combined in many ways*
  - To do *many things*
- Definition and placement of function
  - What to do, and where to do it
- The "division of labor"
  - Across multiple protocols and mechanisms
  - Across components (hosts, routers, administrators)
- Goal: search for general principles
  - Of protocol design, evaluation, and composition

What is a Network Protocol?

- Rules that govern communication
  - How to identify the devices and establish connectivity
  - Message format (syntax) and meaning (semantics)
- Distributed solution to a problem
  - Deliver an ordered, reliable stream of bytes
  - Share link or network bandwidth fairly
  - Compute a shortest path on a graph
- Tunable platform for network administrators
  - Buffer space for incoming data on receiving hosts
  - Link weights used to compute shortest paths
  - Policies for selecting wide-area Internet paths

Syllabus

- Classic Congestion Control
- Specialized Congestion Control (Multimedia)
- Data Plane
- Interdomain Routing
- ML for Networking
- Networking for ML
- Compositional Network Architecture

Structure of the Course

- Reading and analyzing research papers
  - Design and evaluation of network protocols
  - Summaries, critiques, and comparisons of the papers
- Classroom time
  - Instructor and Student-led Discussion and debate about the research papers. Perusall before, “reflection” after.
- Final research project
  - Research with a system-building component

Course Logistics: Semester Project

- Individual Semester project
  - Open-ended, novel research problem throughout semester
  - Must involve writing substantial software
  - Example topics inspired by readings, discussion
  - **I provide Claude Code org, and encourage its use!**
- Can overlap with other projects, with permission
  - Undergraduate independent work
  - Graduate student research projects
  - Must be related to 561 scope, instructor approves
- Deliverables
  - Proposal: Initial- Sep 25, Final- Oct 16
  - Code Review Check-in: TBA
  - Code Feature-Complete and Review: Dec 4
  - Medium Blog Posts: Dec 15 (Dean's Date)

Grading

- Class participation (30%)
  - Discussion in class is important! Speak up!!
  - Paper reviews presented in class
  - Online reviews of project videos and papers
- Semester project (60%)
  - Proposal, video presentation, and final report

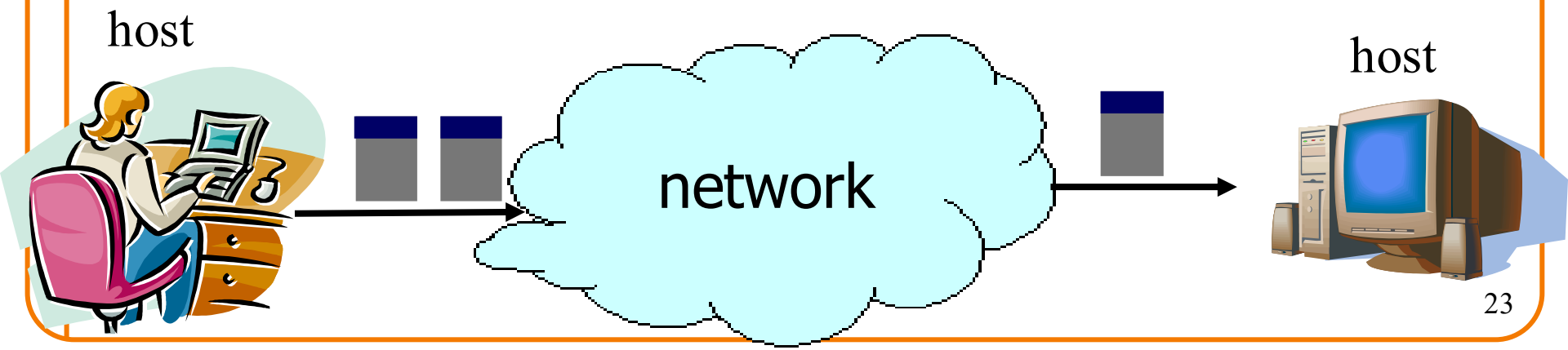
Getting Started…

1. Best-effort packet delivery service
2. Modularity through layering
3. Directories and routing
4. Data, control, and management planes

Best-Effort Packet-Delivery Service

Host-Network Division of Labor

- Packet switching
  - Divide messages into a sequence of packets
  - Headers with source and destination address
- Best-effort delivery
  - Packets may be lost
  - Packets may be corrupted
  - Packets may be delivered out of order



Host-Network Interface: Why Packets?

- Data traffic is bursty
  - Logging in to remote machines
  - Exchanging e-mail messages
- Don't want to waste bandwidth
  - No traffic exchanged during idle periods
- Better to allow multiplexing
  - Different transfers share access to same links
- Packets can be delivered by most anything
  - RFC 1149: IP Datagrams over Avian Carriers

Host-Network Interface: Why Best-Effort?

- Never having to say you're sorry…
  - Don't reserve bandwidth and memory
  - Don't do error detection & correction
  - Don't remember from one packet to next
- Easier to survive failures
  - Transient disruptions are okay during failover
- Can run on nearly any link technology
  - Greater interoperability and evolution

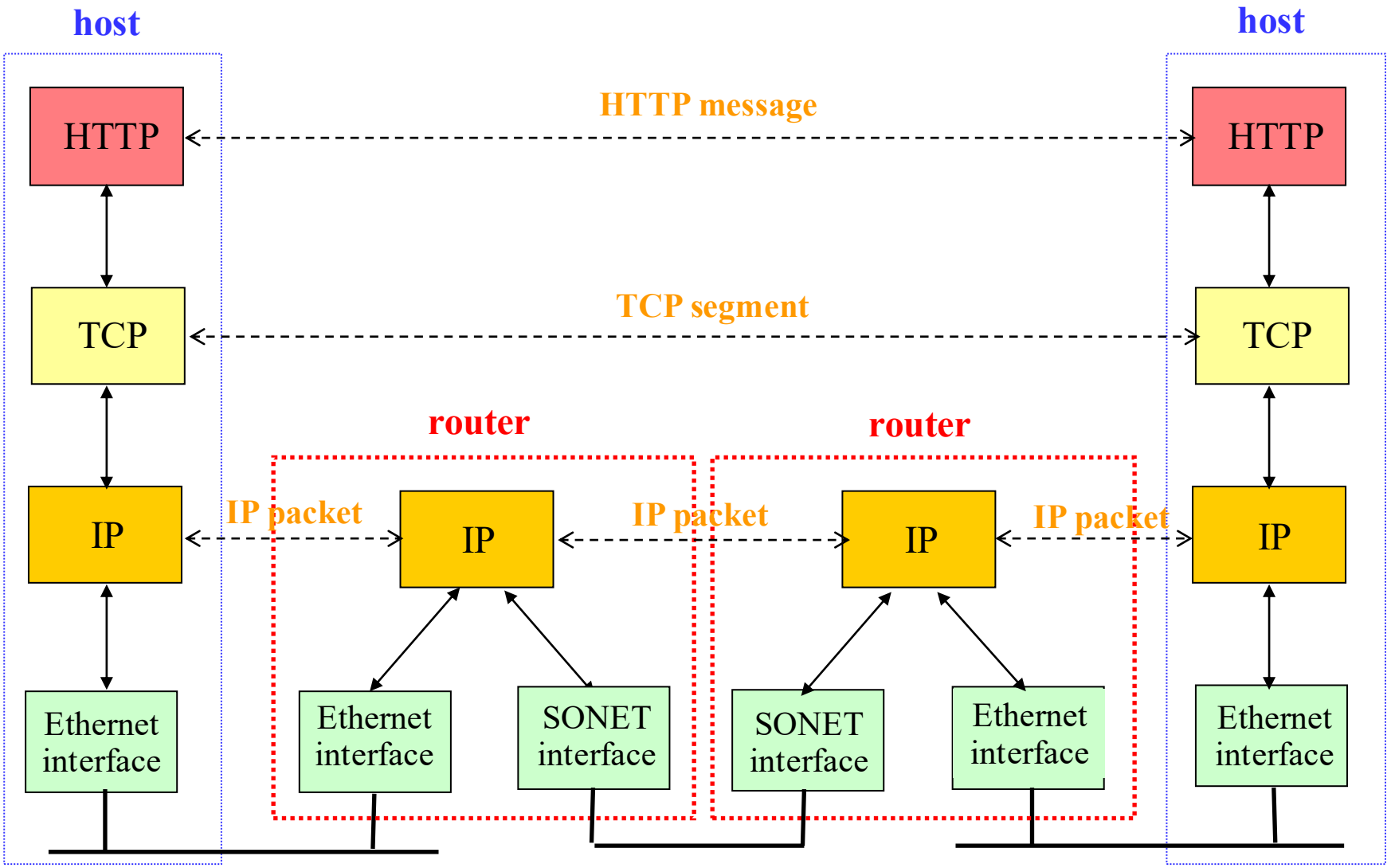
Intermediate Transport Layer

- But, *applications* want efficient, accurate transfer of data in order, in a timely fashion
  - Let the end hosts handle all of that
  - (An example of the "end-to-end argument")
- Transport layer can optionally…
  - Detect and retransmit lost packets
  - Put out-of-order packets back in order
  - Detect and handle corrupted packets
  - Avoid overloading the receiver
  - <insert your requirement here>

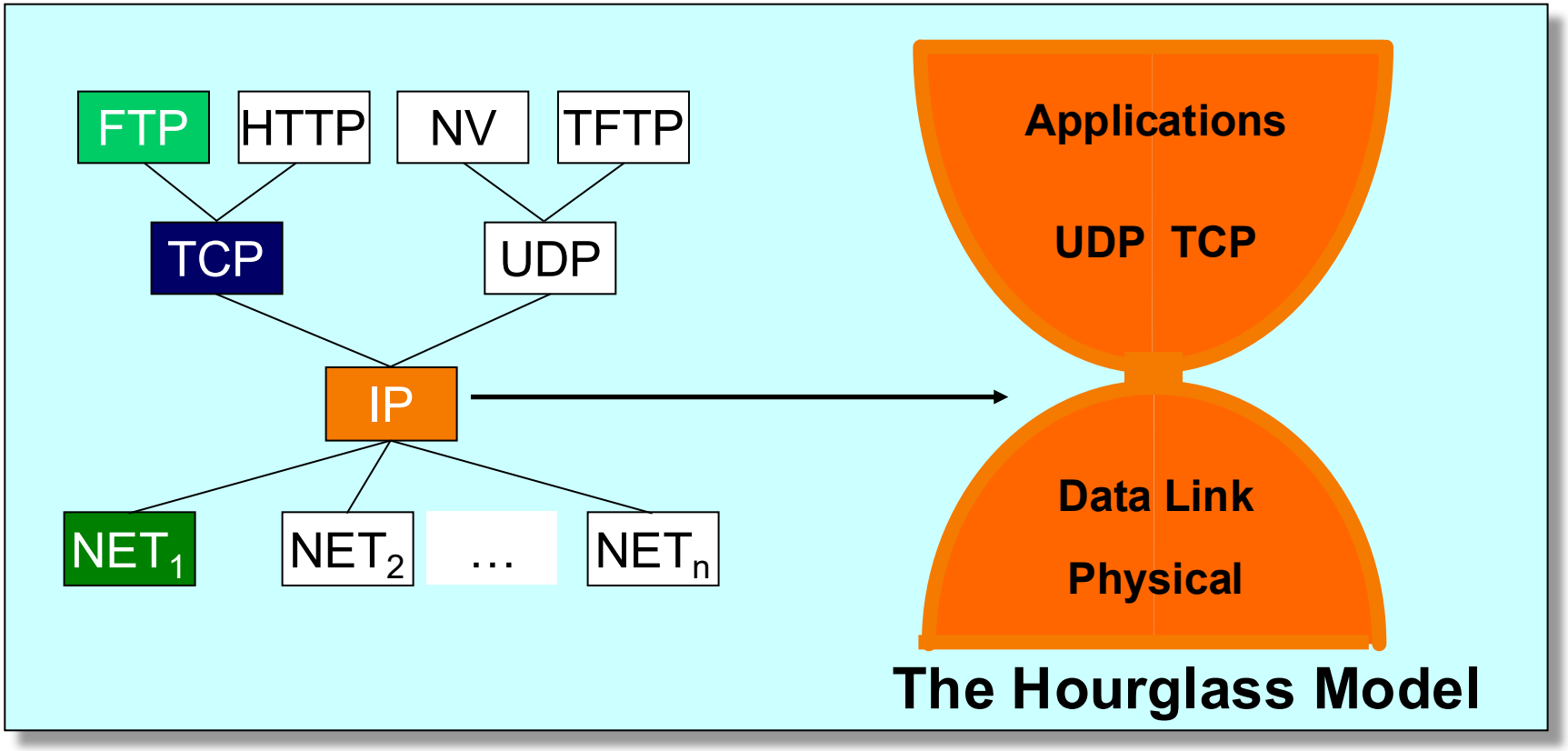
Modularity Through Layering

IP Protocol Stack

IP Suite: End Hosts vs. Routers

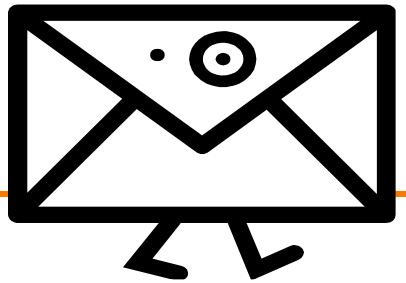


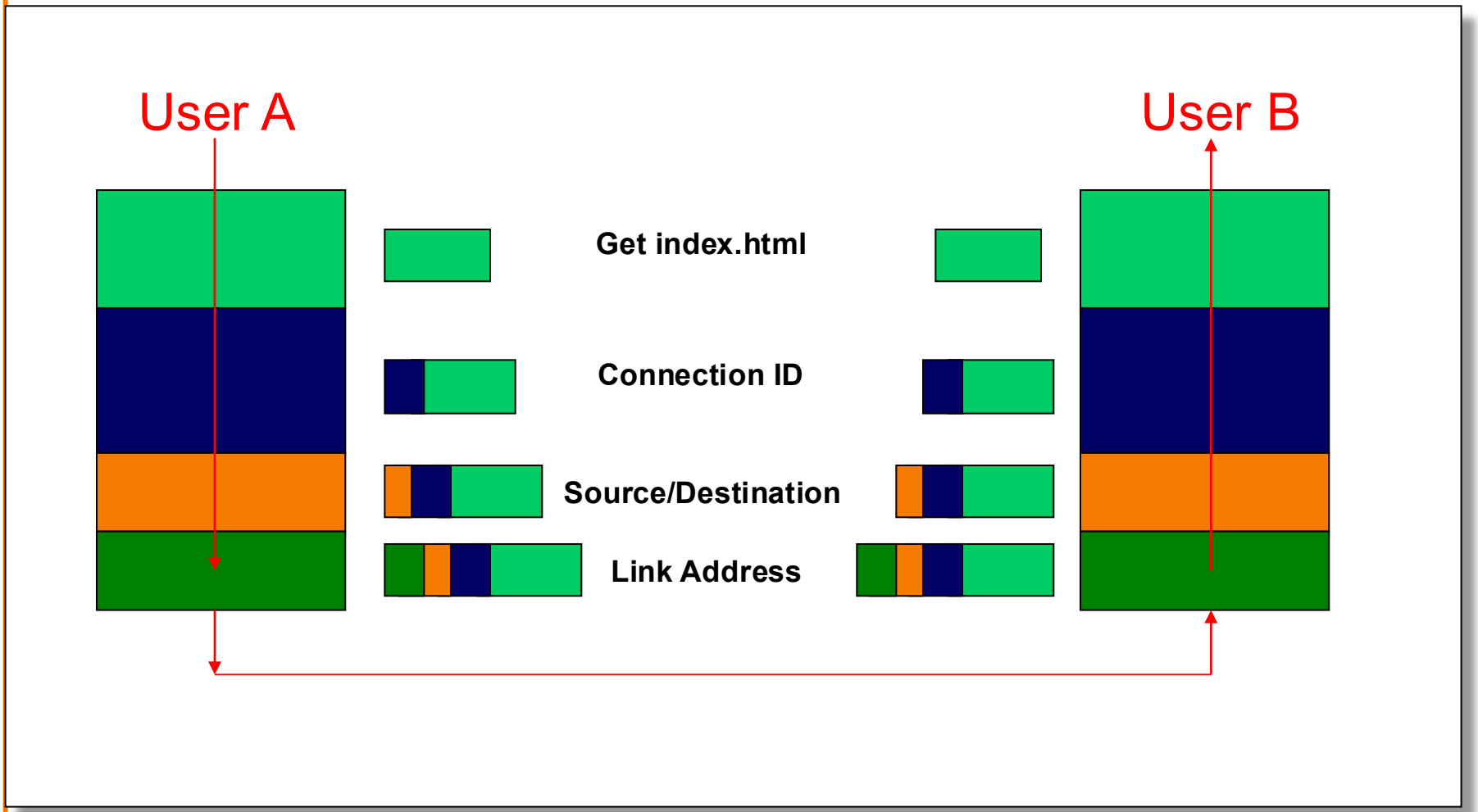
The Narrow Scope of IP



IP facilitates interoperability

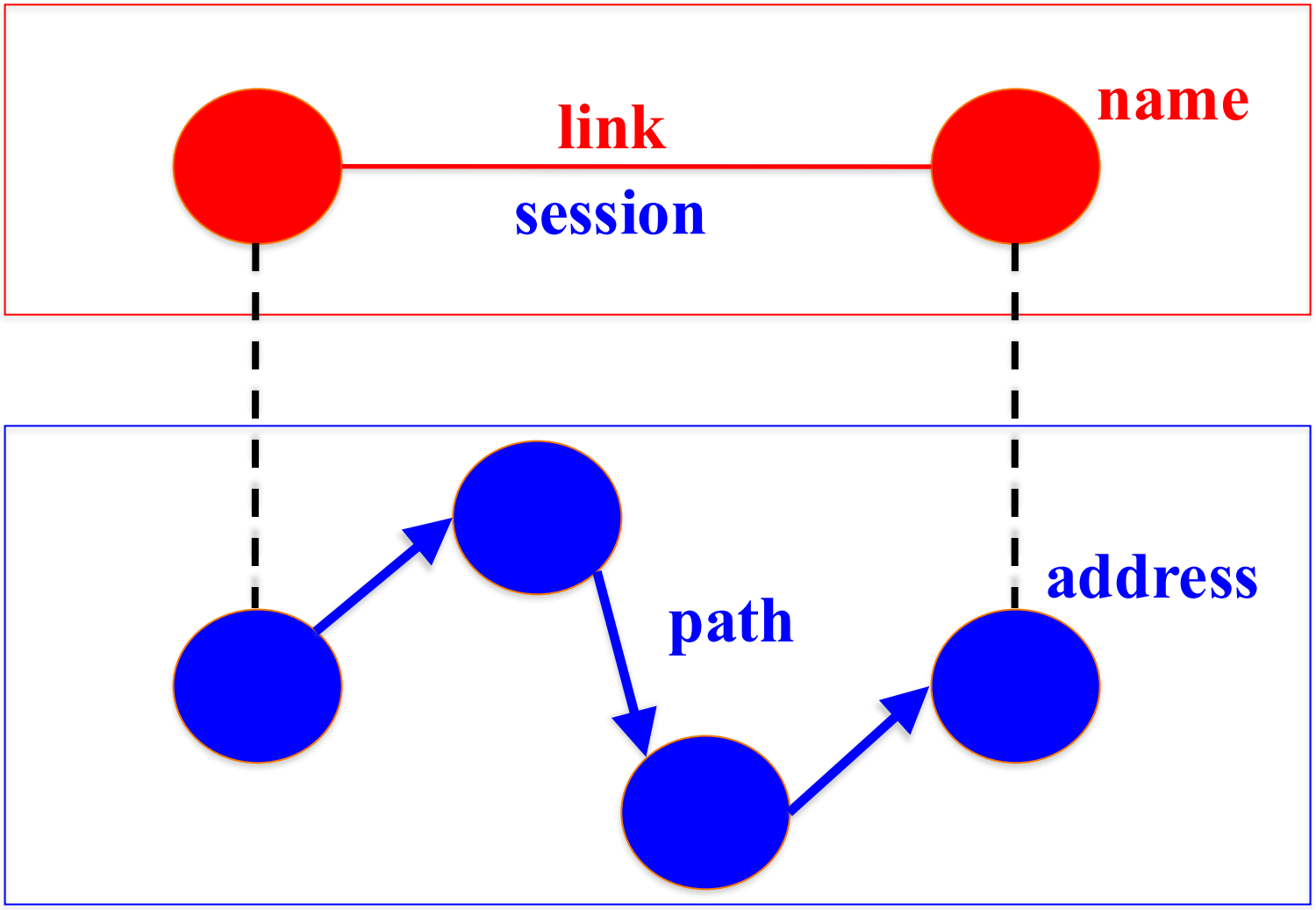
Layer Encapsulation



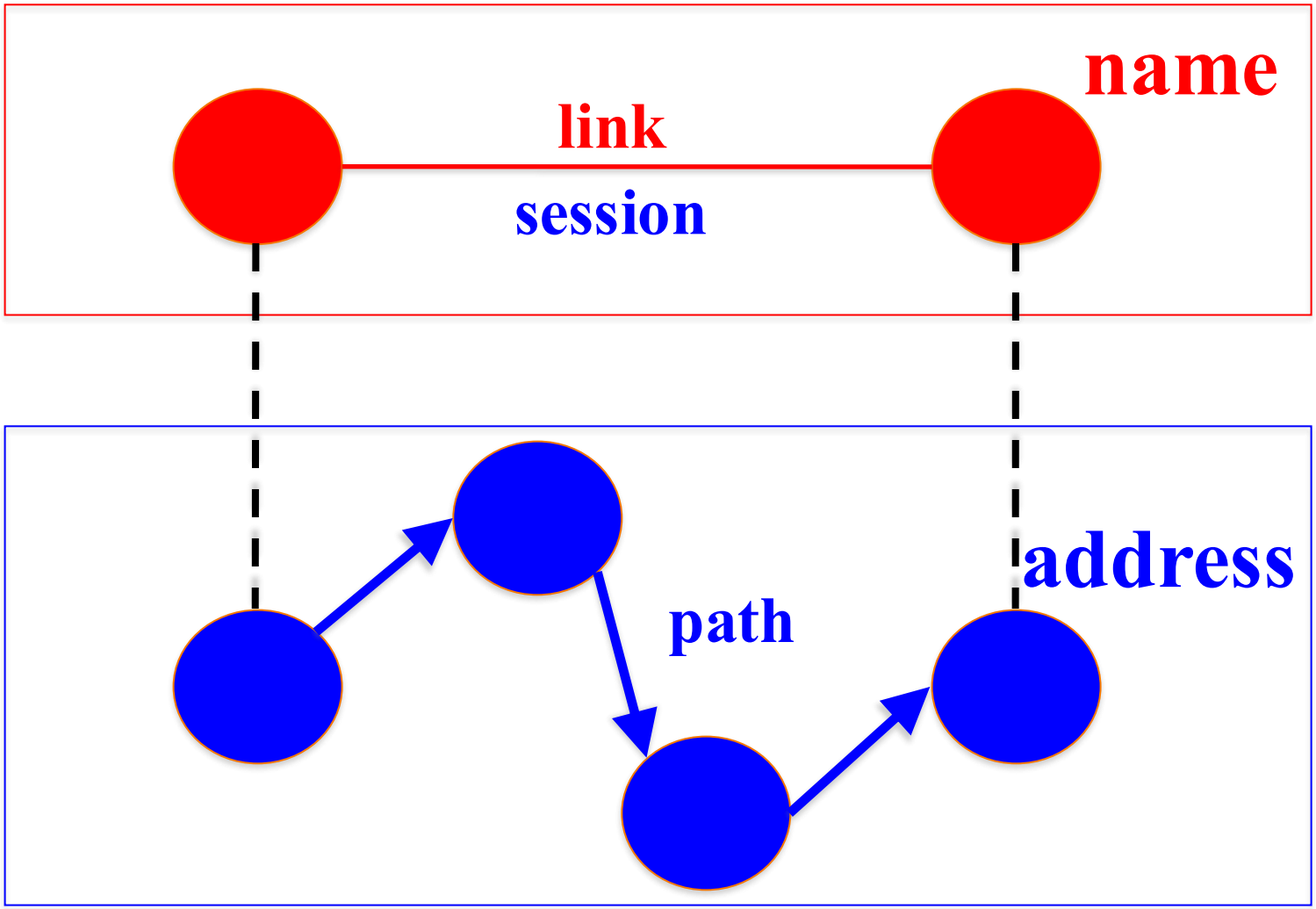


Directories and Routing

Relationship Between Layers



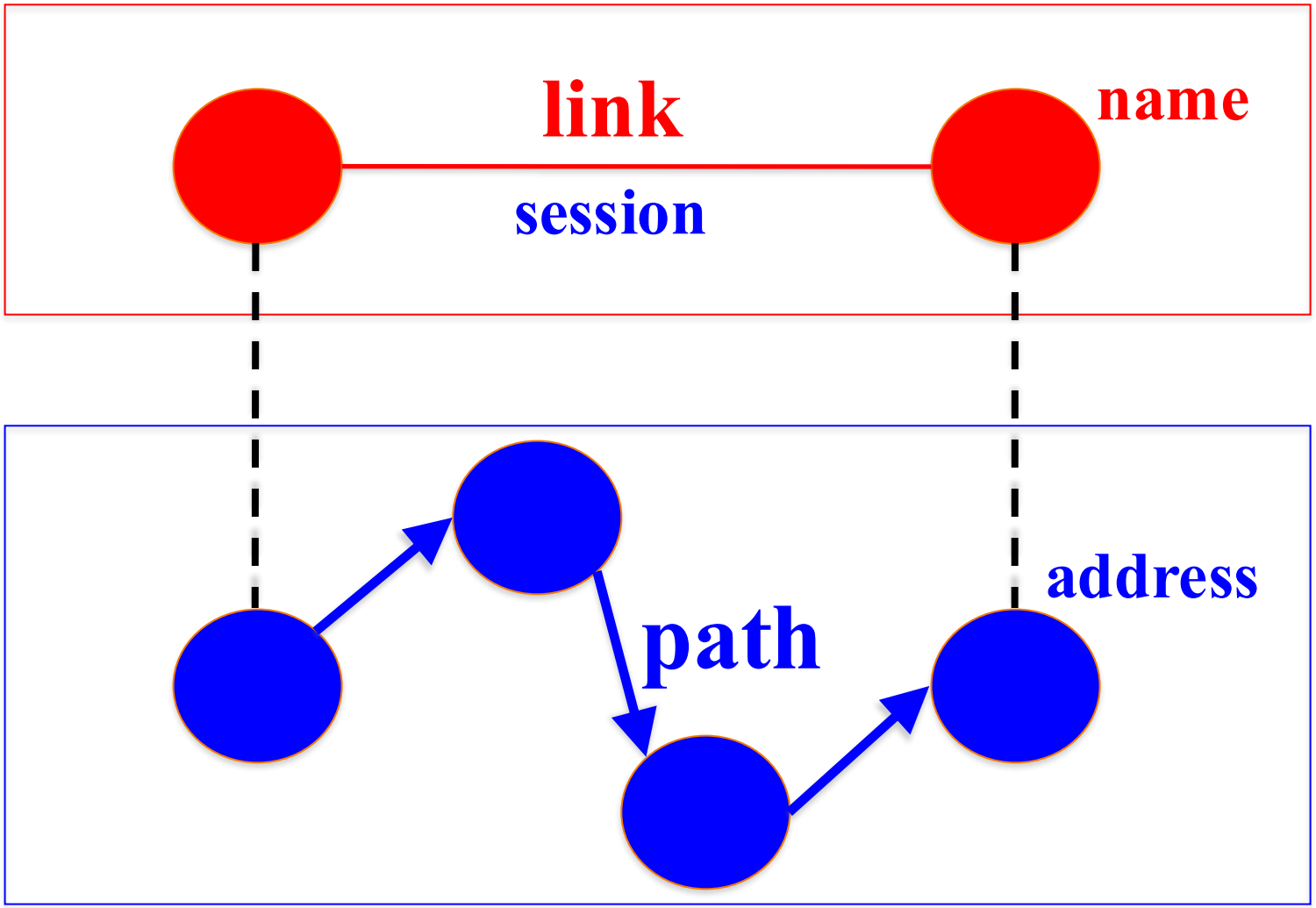
Directories: Mapping Name to Address



Types of Directories

- Simplistic designs
  - Ask everyone (e.g., flooding in ARP)
  - Tell everyone (e.g., pushing /etc/hosts)
  - Central directory
- Scalable distributed designs
  - Hierarchical namespace (e.g., DNS)
  - Flat name space (e.g., Distributed Hash Table)

Routing: Mapping Link to Path

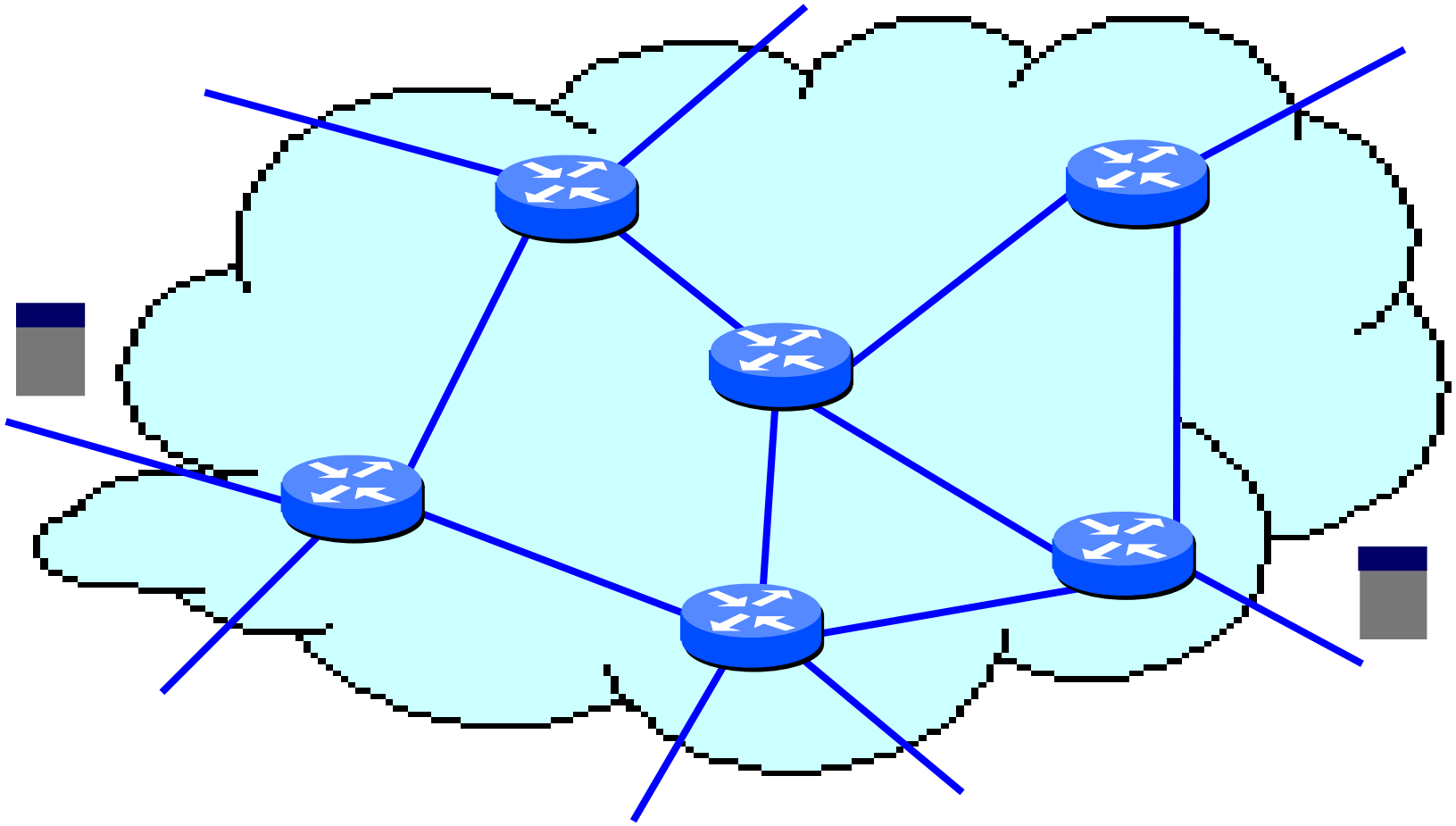


Path Computation

- Spanning tree (e.g., Ethernet)
  - One tree that connects every pair of nodes
- Shortest paths (e.g., OSPF, IS-IS, RIP)
  - Shortest-path tree rooted at each node
- Locally optimal paths (e.g., BGP)
  - Each node selects the best among its neighbors
- End-to-end paths (e.g., source routing)
  - Each node picks the best end-to-end path

Data, Control, and Management Planes

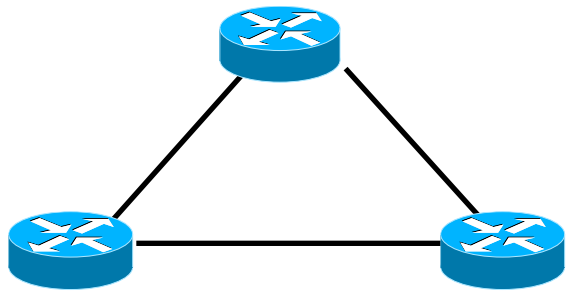
Inside the Network



Forward packets from the sender to the receiver

Split into Data vs. Control Plane

- Data plane: packets
  - Handle individual packets as they arrive
  - Forward, drop, or buffer
  - Mark, shape, schedule, …

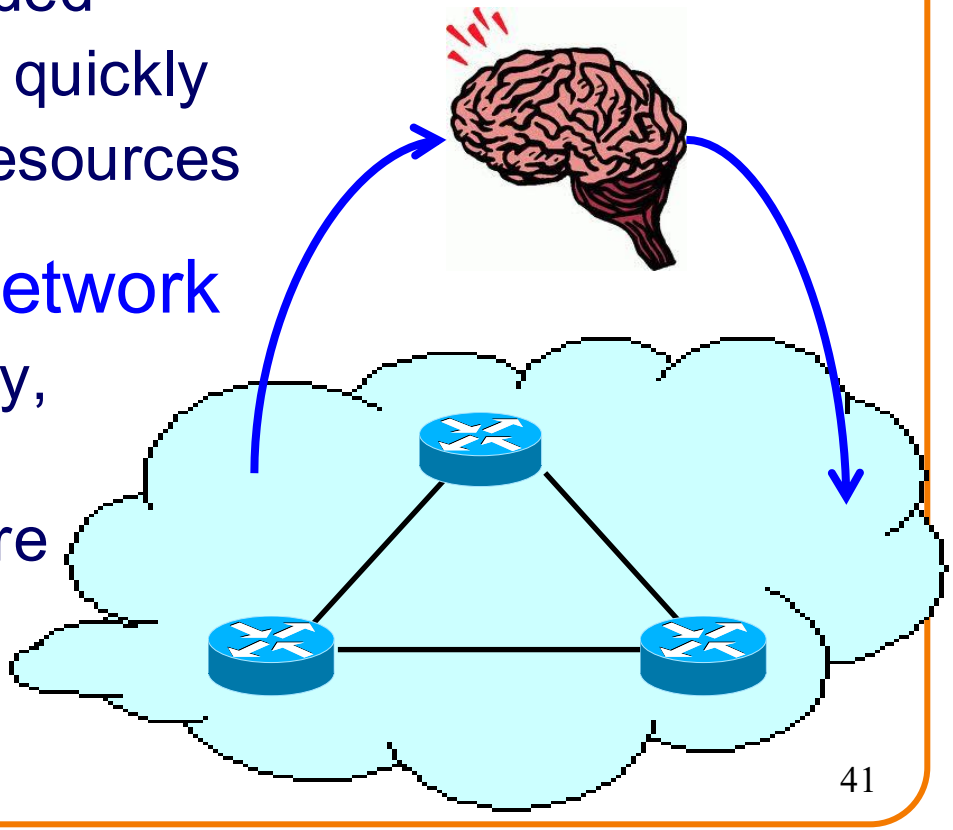


- Control plane: events
  - Track changes in network topology
  - Compute paths through the network
  - Reserve resources along a path

Motivated by need for high-speed packet forwarding

Adding the Management Plane

- Making the network run *well*
  - Traffic reaches the right destination
  - Traffic flows over short, uncongested paths
  - Unwanted traffic is discarded
  - Failure recovery happens quickly
  - Routers don't run out of resources
- A control loop with the network
  - Measure (sense): topology, traffic, performance, …
  - Control (actuate): configure control and data planes



How to Read

You May Think You Already Know
How To Read, But…

You Spend a Lot of Time Reading

- Reading for grad classes
- Reviewing conference submissions
- Giving colleagues feedback
- Keeping up with your field
- Staying broadly educated
- Transitioning into a new areas
- Learning how to write better papers ☺

It is worthwhile to learn to read *effectively*

Keshav's Three-Pass Approach: Step 1

- A ten-minute scan to get the general idea
  - Title, abstract, and introduction
  - Section and subsection titles
  - Conclusion and bibliography
- What to learn: the five C's
  - Category: What type of paper is it?
  - Context: What body of work does it relate to?
  - Correctness: Do the assumptions seem valid?
  - Contributions: What are the main research contributions?
  - Clarity: Is the paper well-written?
- Decide whether to read further…

Keshav's Three-Pass Approach: Step 2

- A more careful, one-hour reading
  - Read with greater care, but ignore details like proofs
  - Figures, diagrams, and illustrations
  - Mark relevant references for later reading
- Grasp the content of the paper
  - Be able to summarize the main idea
  - Identify whether you can (or should) fully understand
- Decide whether to
  - Abandon reading in greater depth
  - Read background material before proceeding further
  - Persevere and continue for a third pass

Keshav's Three-Pass Approach: Step 3

- Several-hour virtual re-implementation of the work
  - Making the same assumptions, recreate the work
  - Identify the paper's innovations and its failings
  - Identify and challenge every assumption
  - Think how you would present the ideas yourself
  - Jot down ideas for future work
- When should you read this carefully?
  - Reviewing for a conference or journal
  - Giving colleagues feedback on a paper
  - Understanding a paper closely related to your research
  - Deeply understanding a classic paper in the field

Other Tips for Reading Papers

- Read at the right level for what you need
  - "Work smarter, not harder"
- Read at the right time of day
  - When you are fresh, not sleepy
- Read in the right place
  - Where you are not distracted, and have enough time
- Read actively
  - With a purpose (what is your goal?)
  - With a pen or computer to take notes
- Read critically
  - Think, question, challenge, critique, …