CS 5114
Network Programming Languages
End Hosts

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Based on lecture notes by Jennifer Rexford and Michael Freedman

Announcements

Signup Sheet: breakfast pickup and presentations

Reviews: start next week!

- Only review one paper but please read them all!
- Structure: summary, strengths, weaknesses, discussion
- Aim to write about half a page to one page
- Submit by email or hand in at the start of class

Projects

- Groups and initial proposal by Feb 19th
- Full proposals due March 14th
- Final reports and presentations due on May 2nd

Next Few Classes: Overview

Host

- Network discovery and bootstrapping
- Resource allocation and interface to applications

Data plane

- Streaming algorithms and switch fabric
- Forward, filter, buffer, schedule, mark, monitor, …

Control plane

- Distributed algorithms for computing paths
- Disseminating the addresses of end hosts

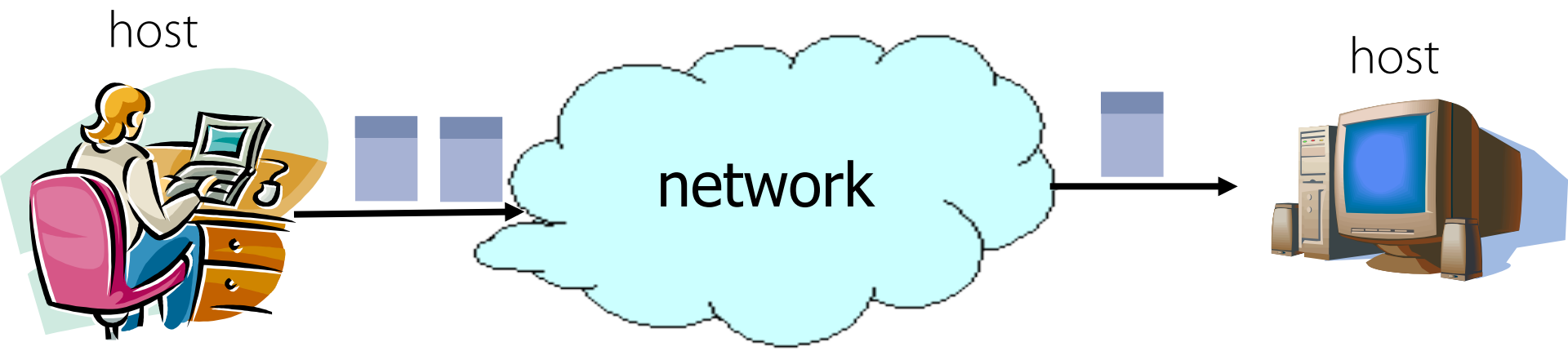
Host-Network Division of Labor

Network

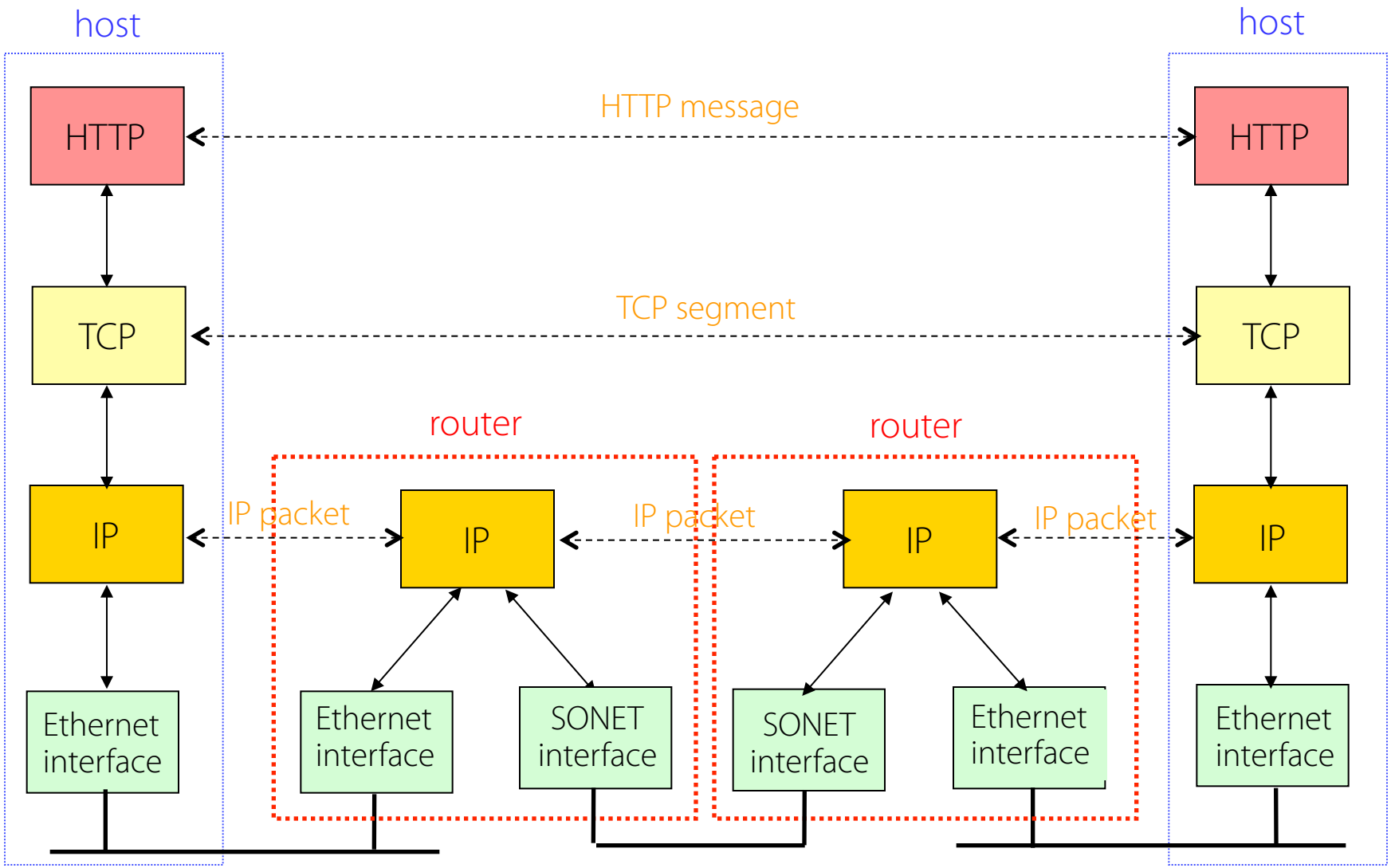
- Best-effort packet delivery
- Between two (or more) end-point addresses

Hosts

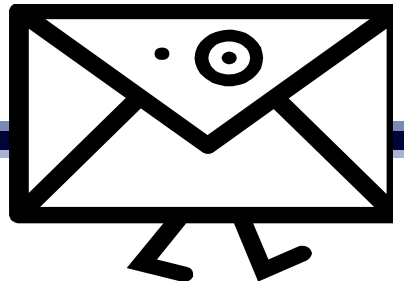
- Everything else

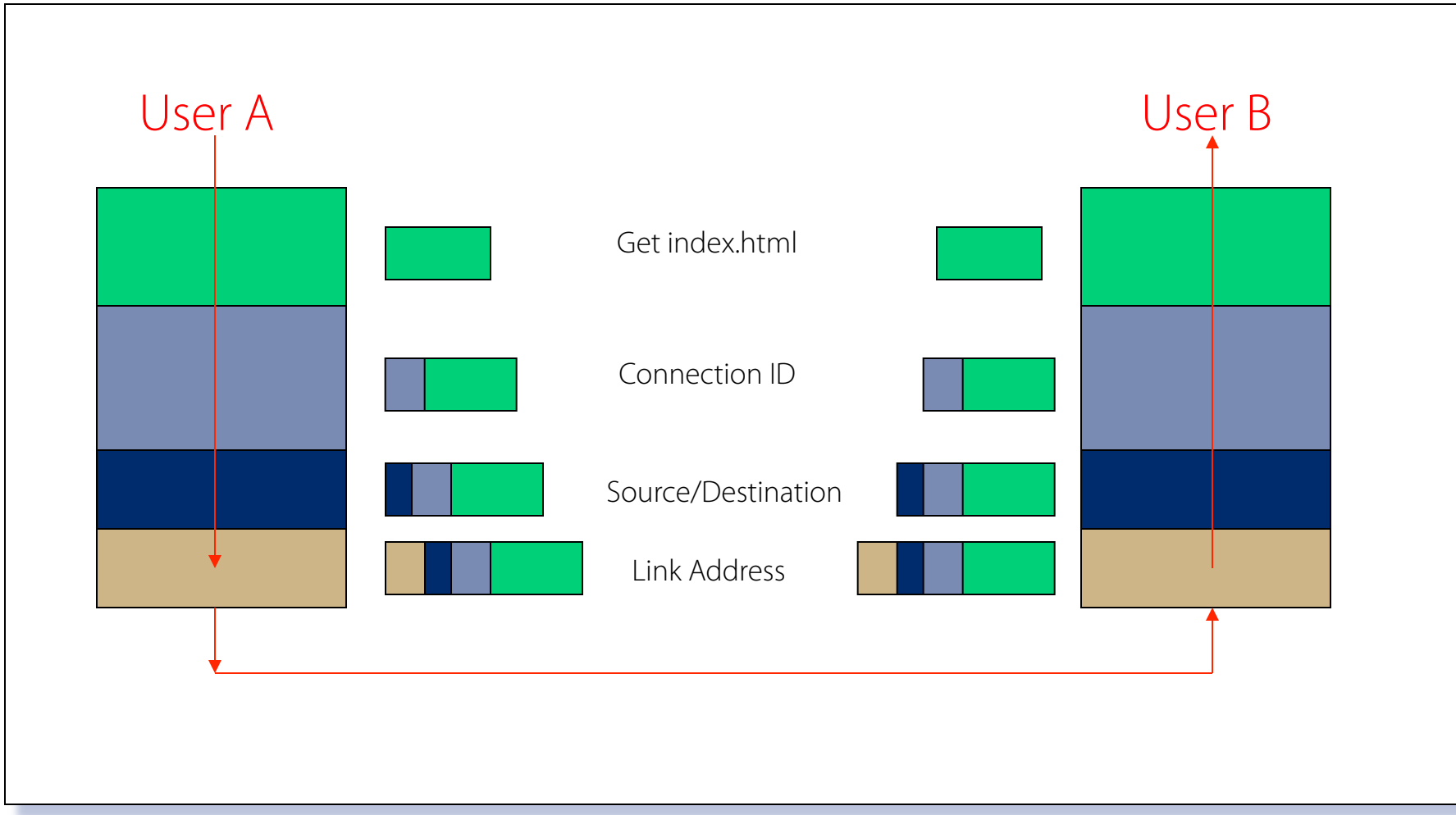


IP Suite: End Hosts vs. Routers

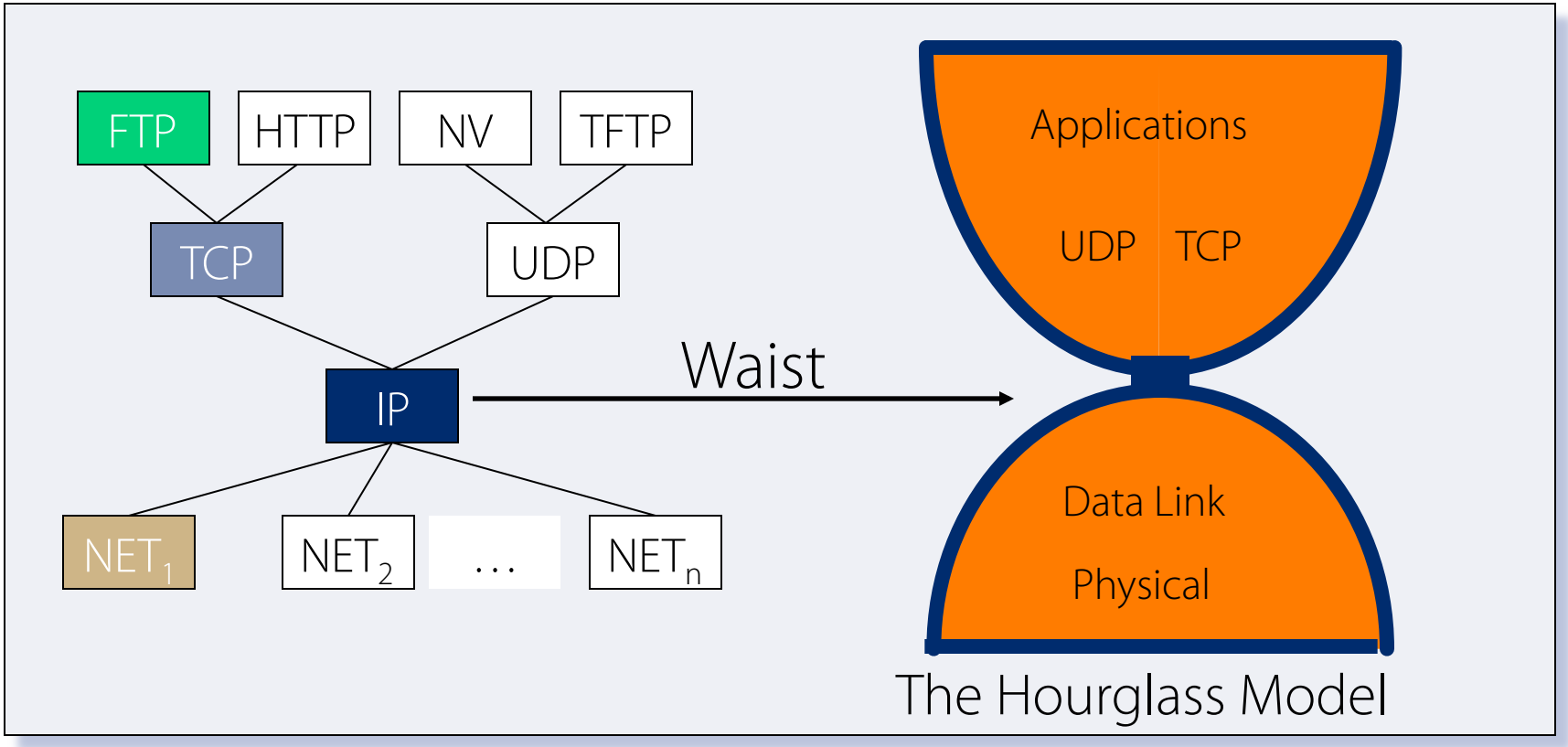


Layer Encapsulation





The "Narrow Waist" of the Internet



The narrow waist facilitates interoperability

The Role of the End Host

Network discovery and bootstrapping

- How does the host join the network?
- How does the host get an address?

Interface to networked applications

- What interface to higher-level applications?
- How does the host realize that abstraction?

Distributed resource sharing

- What roles does the host play in network resource allocation decisions?

Network Discovery and Bootstrapping

Three Kinds of Identifiers

	Host Name	IP Address	MAC Address
Example	www.cs.cornell.edu	132.236.204.10	00-15-C5-49-04-A9
Size	Hierarchical, human readable, variable length	Hierarchical, machine readable, 32 bits	Flat, machine readable, 48 bits
Read by	Humans, hosts	IP routers	Switches in LAN
Allocation, top-level	Domain, assigned by registrar (e.g., for .edu)	Variable-length prefixes, assigned by ICANN, RIR, or ISP	Fixed-sized blocks, assigned by IEEE to vendors (e.g., Dell)
Allocation, low-level	Host name, local administrator	Interface, by admin or DHCP	Interface, by vendor

Mapping Between Identifiers

Dynamic Host Configuration Protocol (DHCP)

- Given a MAC address, assigns a unique IP address
- … and gives host other information about the local network (e.g., gateway)
- Automates the boot-strapping process

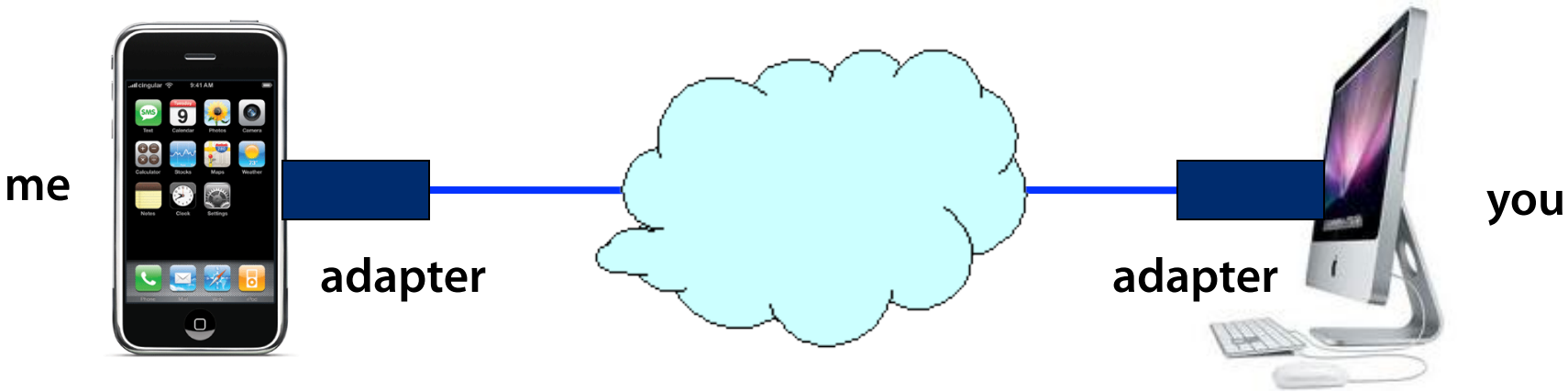
Address Resolution Protocol (ARP)

- Given an IP address, provides the MAC address
- Enables communication within the local network

Domain Name System (DNS)

- Given a host name, provides the IP address
- Given an IP address, provides the host name

Learning a Host's Address



Who am I?

- Hard-wired: MAC address
- Static configuration: IP interface configuration
- Dynamically learned: IP address configured by DHCP

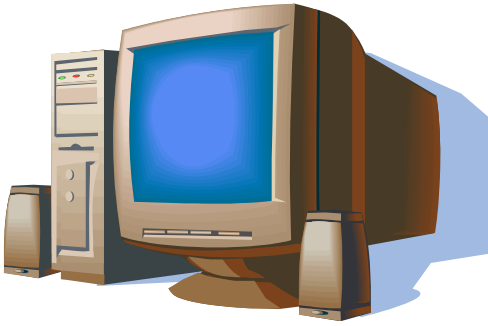
Who are you?

- Hard-wired: IP address in a URL, or in the code
- Dynamically looked up: ARP or DNS

Dynamic Host Configuration Protocol

new client

DHCP discover (broadcast)



DHCP server

DHCP offer

Host learns
IP address,
Subnet mask,
Gateway address, DNS server(s), and a lease time.

DHCP request (broadcast)

DHCP ACK

Address Resolution Protocol (ARP)

Every host maintains an ARP table

- (IP address, MAC address) pair

Consult the table when sending a packet

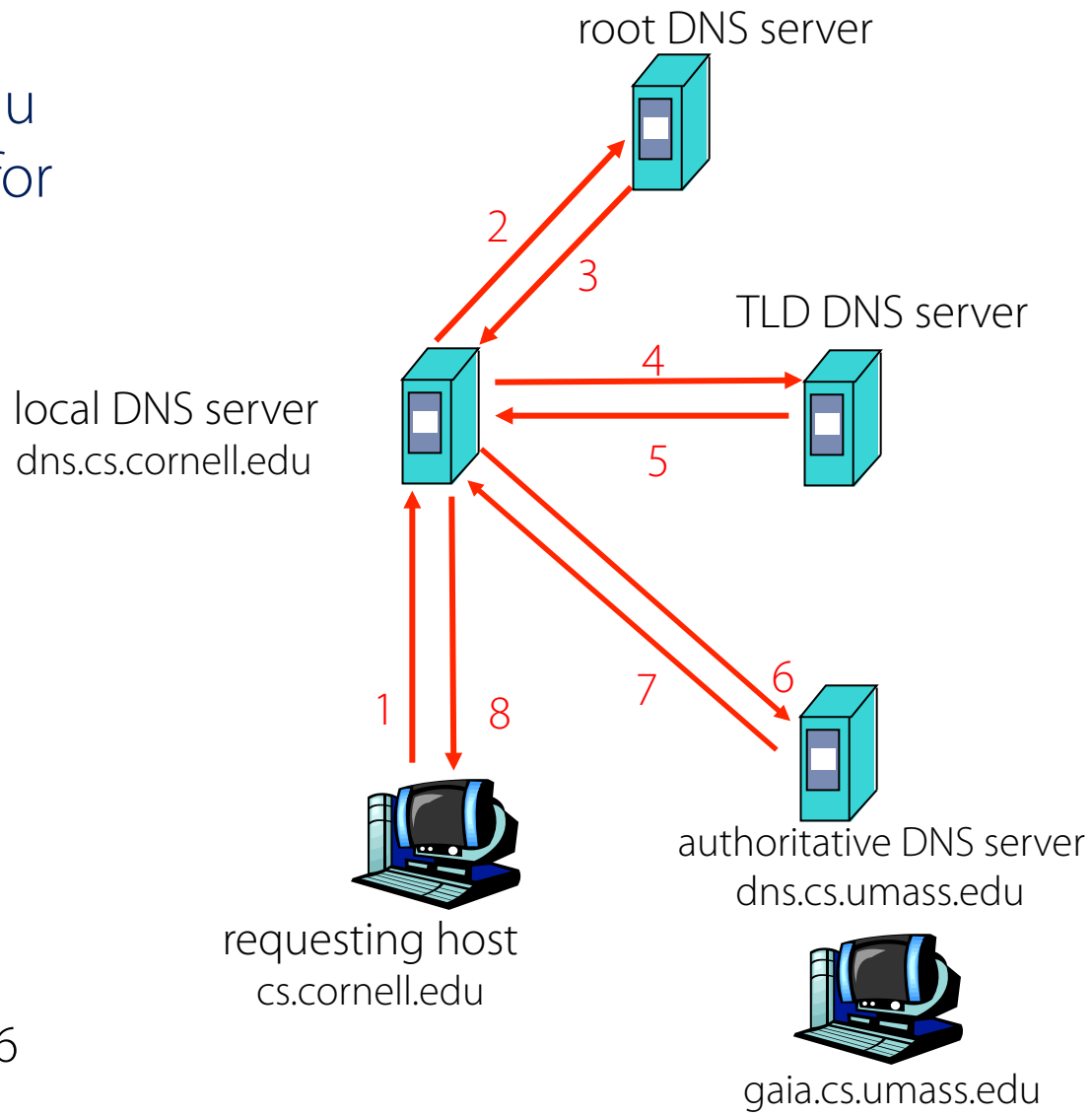
- Map destination IP address to destination MAC address
- Encapsulate and transmit the data packet

But, what if the IP address is not in the table?

- Sender broadcasts: "Who has IP address 1.2.3.156?"
- Receiver responds: "MAC address 58-23-D7-FA-20-B0"
- Sender caches the result in its ARP table

Domain Name System

Host at cs.cornell.edu
wants IP address for
gaia.cs.umass.edu



Recursive query: #1
Iterative queries: #2, 4, 6

Questions

Should addresses correspond to the interface (point of attachment) or to the host?

Why have three identifiers? Do we need them all?

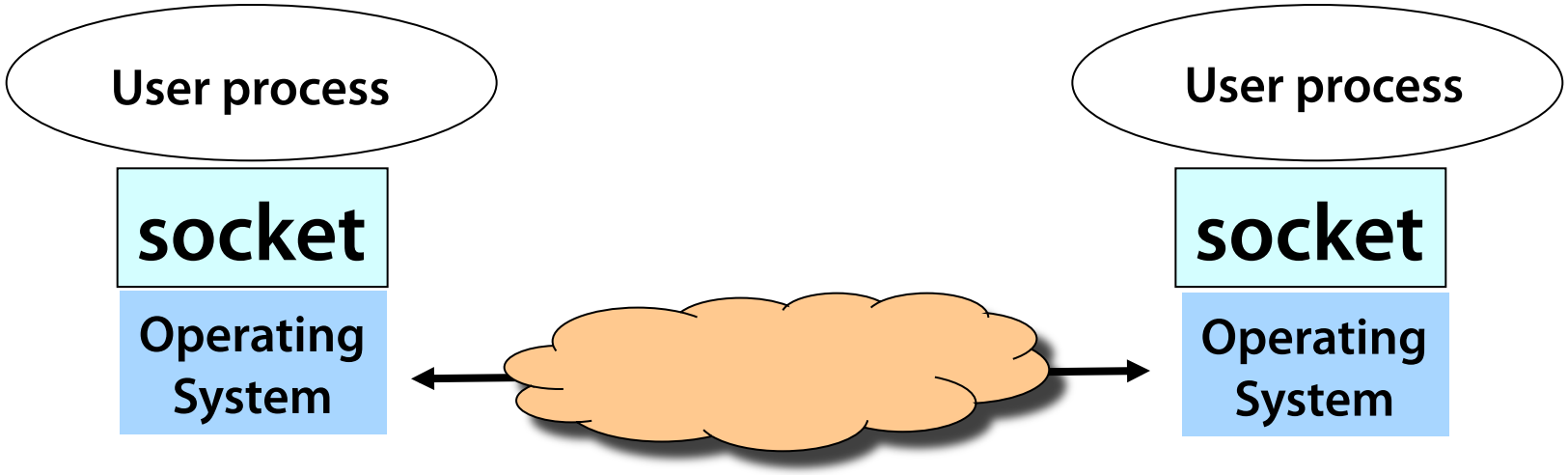
What should be done to prevent address spoofing?

Interface to Applications

Socket Abstraction

Best-effort packet delivery is a clumsy abstraction

- Applications typically want higher-level abstractions
- Messages, uncorrupted data, reliable in-order delivery

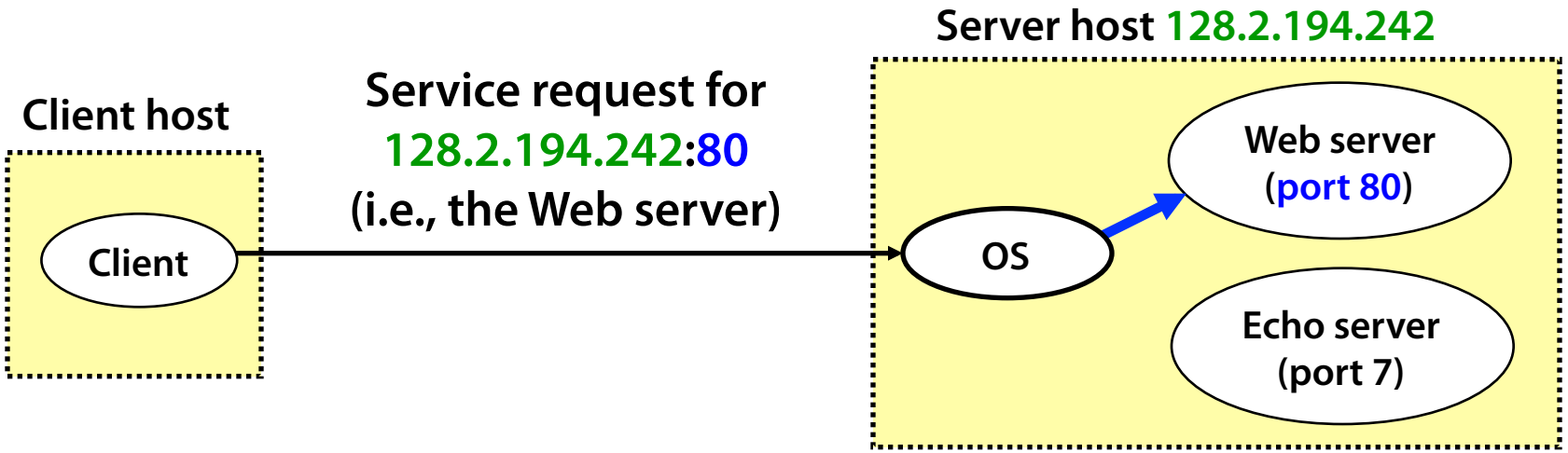


Applications communicate using "sockets"

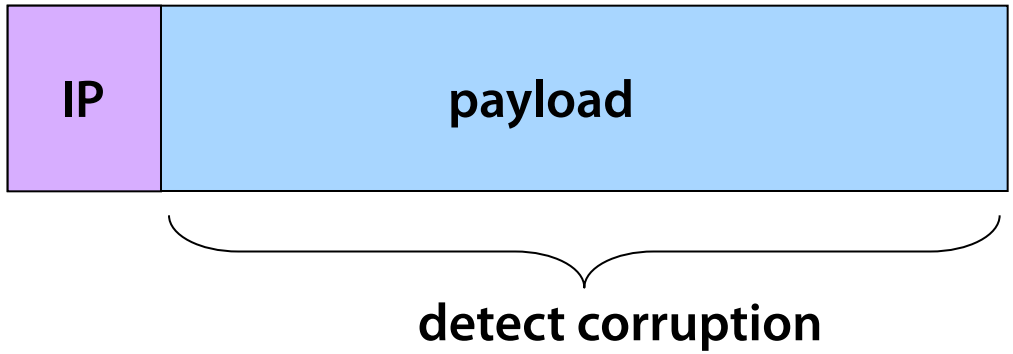
- Stream socket: reliable stream of bytes (like a file)
- Message socket: unreliable message delivery

Two Basic Transport Features

Demultiplexing: port numbers



Error detection: checksums



Two Main Transport Layers

User Datagram Protocol (UDP)

- Just provides demultiplexing and error detection
- Header fields: port numbers, checksum, and length
- Low overhead, good for query/response and multimedia

Transmission Control Protocol (TCP)

- Provides a "stream of bytes" abstraction
- Retransmits lost or corrupted data
- Puts out-of-order data back in order
- Adapts the sending rate to alleviate congestion
- Higher overhead, good for most stateful applications

Questions

Is a socket between IP addresses the right abstraction?

- Mobile hosts?
- Replicated services?

What does the network know about the traffic?

- Inferring the application from the port numbers?

Is end-to-end error detection/correction the right model?

- High loss environments?
- Expense of retransmitting over the entire path?

Distributed Resource Sharing

Resource Allocation Challenges

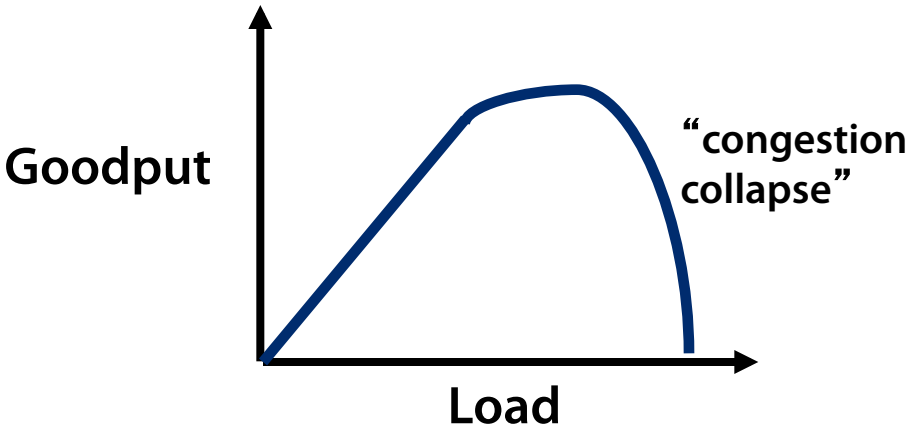
Best-effort network easily becomes overloaded

- No mechanism to "block" excess calls
- Instead excess packets are simply dropped

Examples

- Shared Ethernet medium: frame collisions
- Ethernet switches and IP routers: full packet buffers

Quickly leads to congestion collapse



Increase in load that results in a *decrease* in useful work done.

End Hosts Adjusting to Congestion

End hosts adapt their sending rates

- In response to network conditions

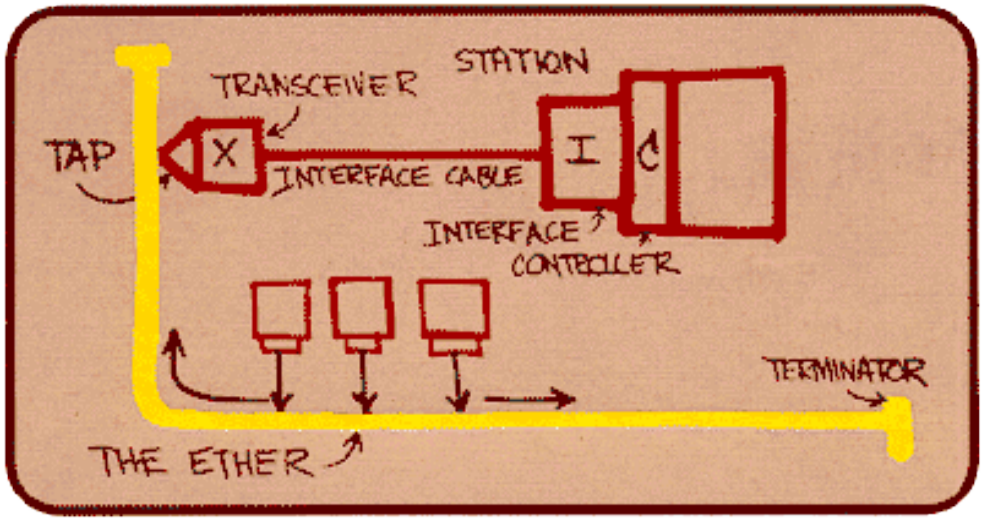
Learning that the network is congested

- Shared Ethernet: carrier sense multiple access
  - Seeing your own frame collide with others
- IP network: observing your end-to-end performance
  - Packet delay or loss over the end-to-end path

Adapting to congestion

- Slowing down the sending rate, for the greater good
- But, host doesn't know how bad things might be…

Ethernet Back-off Mechanism



Carrier sense: wait for link to be idle

- If idle, start sending; if not, wait until idle

Collision detection: listen while transmitting

- If collision: abort transmission, and send jam signal

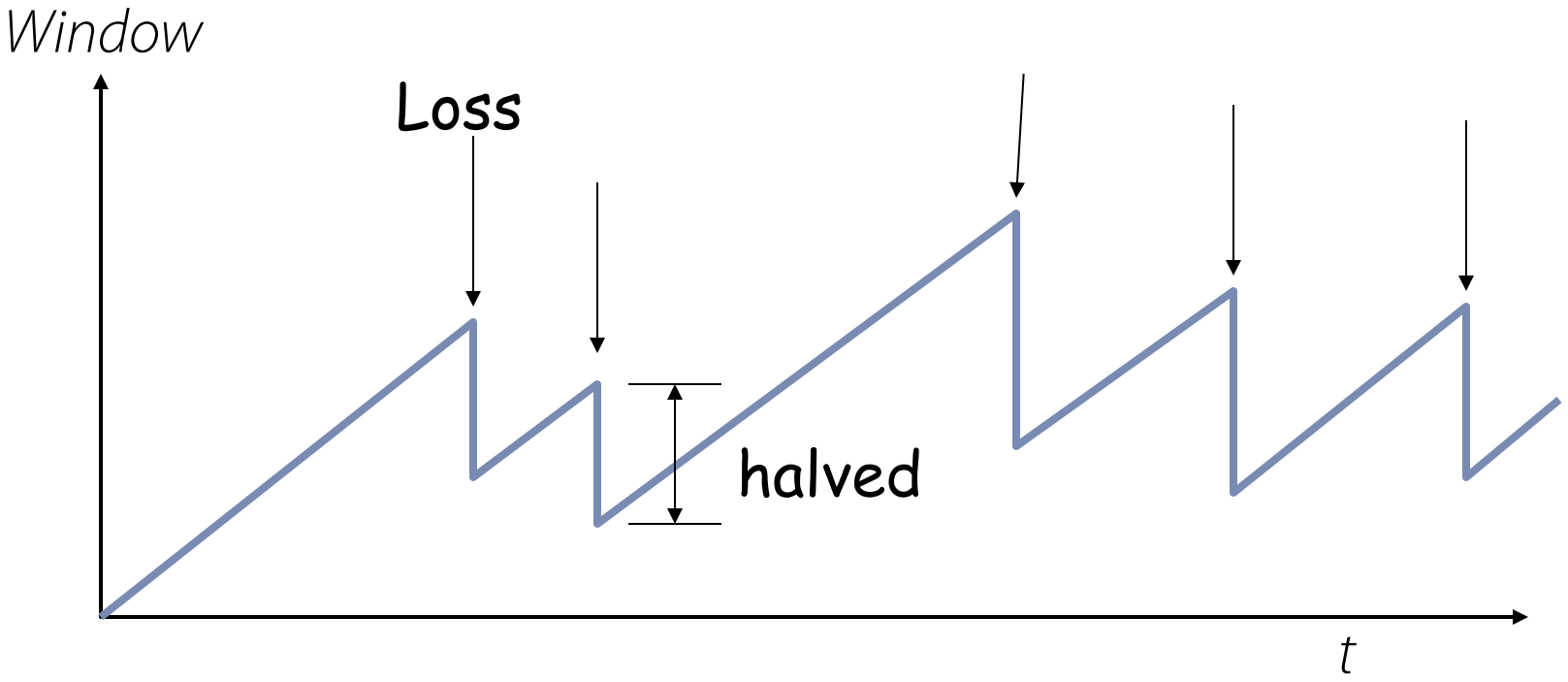
Exponential back-off: wait before retransmitting

- Wait random time, exponentially larger on each retry

TCP Congestion Control

Additive increase, multiplicative decrease

- On packet loss, divide congestion window in half
- On success for last window, increase window linearly



Other mechanisms: slow start, fast retransmit vs. timeout loss, etc.

Questions

What role should the network play in resource allocation?

- Explicit feedback to the end hosts?
- Enforcing an explicit rate allocation?

What is a good definition of fairness?

What about hosts who cheat to hog resources?

- How to detect cheating? How to prevent/punish?

What about wireless networks?

- Difficulty of detecting collisions (due to fading)
- Loss caused by interference, not just congestion

“A Protocol for Packet Network Intercommunication”

(*IEEE Trans. on Communications*, May 1974)

Vint Cerf and Bob Kahn

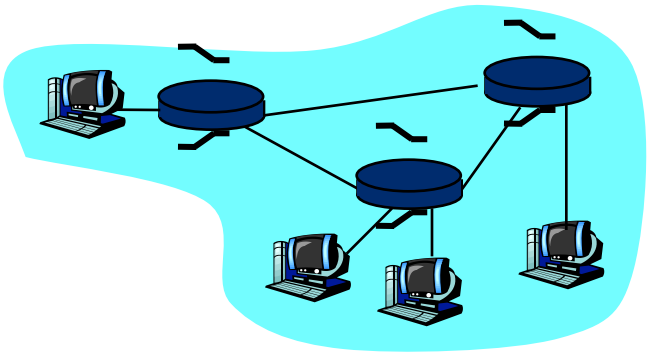
Life in the 1970s…

Multiple unconnected networks

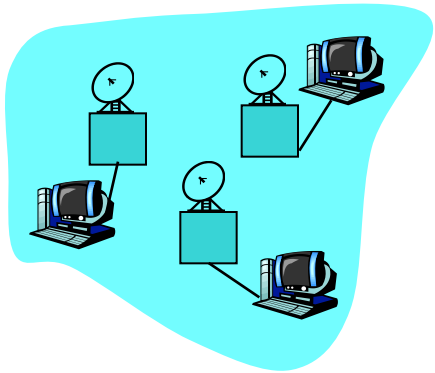
- ARPAnet, data-over-cable, packet satellite (Aloha), packet radio, …

Heterogeneous designs

- Addressing, max packet size, handling of lost/ corrupted data, fault detection, routing, …



ARPAnet



satellite net

Handling Heterogeneity

Where to handle heterogeneity?

- Application process? End hosts? Packet switches?

Compatible process and host conventions

- Obviate the need to support all combinations

Retain the unique features of each network

- Avoid changing the local network components

Introduce the notion of a gateway

Internetwork Layer and Gateways

Internetwork Layer

Internetwork appears as a single, uniform entity

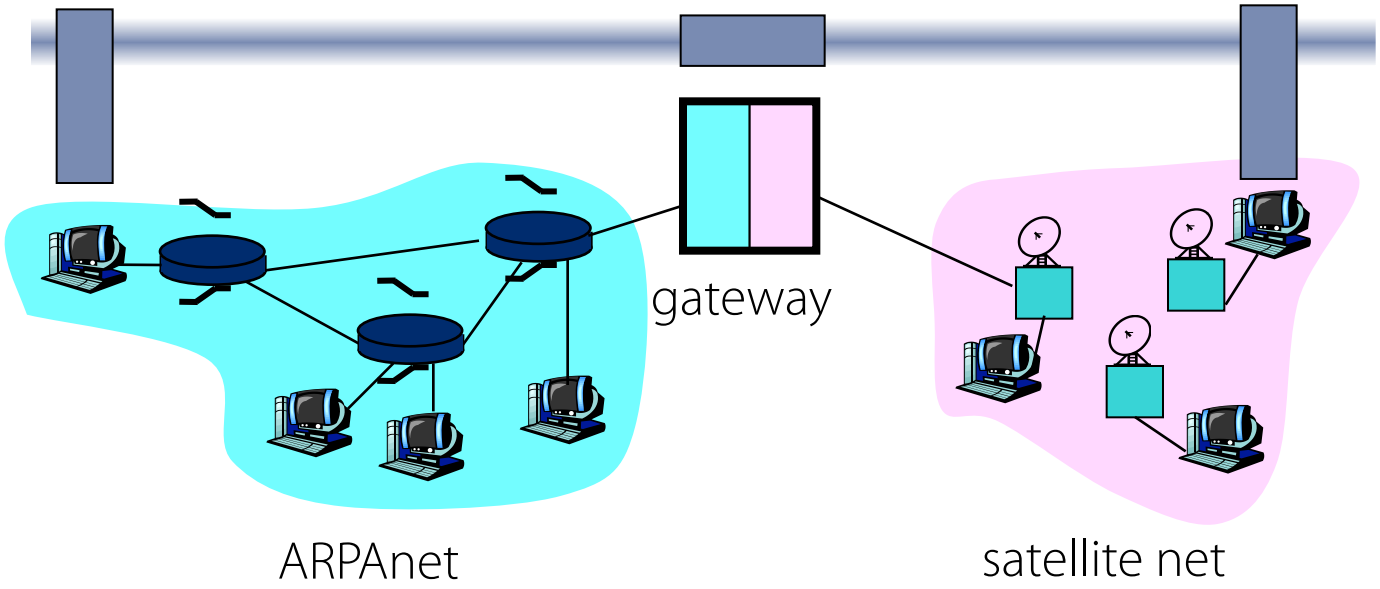
Despite the heterogeneity of the local networks

Network of networks

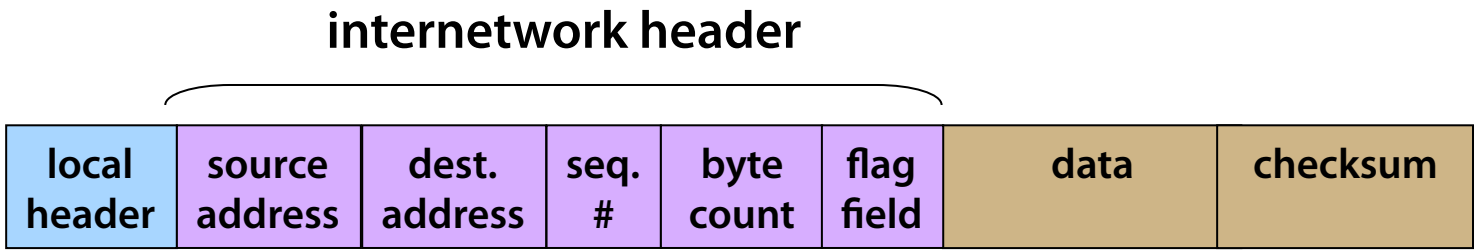
Gateway

"Embed internetwork packets in local packet format or extract them"

Route (at internetwork level) to next gateway



Internetwork Packet Format



Internetwork header in standard format

- Interpreted by the gateways and end hosts

Source and destination addresses

- Uniformly and uniquely identify every host

Ensure proper sequencing of the data

- Include a sequence number and byte count

Enable detection of corrupted text

- Checksum for an end-to-end check on the text

Process-Level Communication

Enable pairs of processes to communicate

- Full duplex
- Unbounded but finite-length messages
- E.g., keystrokes or a file

Key ideas

- Port numbers to (de)multiplex packets
- Breaking messages into segments
- Sequence numbers and reassembly
- Retransmission and duplicate detection
- Window-based flow control

Discussion

What did they get right?

- Which ideas were key to the Internet's success?
- Which decisions still seem right today?

What did they miss?

- Which ideas had to be added later?
- Which decisions seem wrong in hindsight?

What would you do in a clean-slate design?

- If your goal wasn't to support communication between disparate packet-switched networks
- Would you do anything differently?

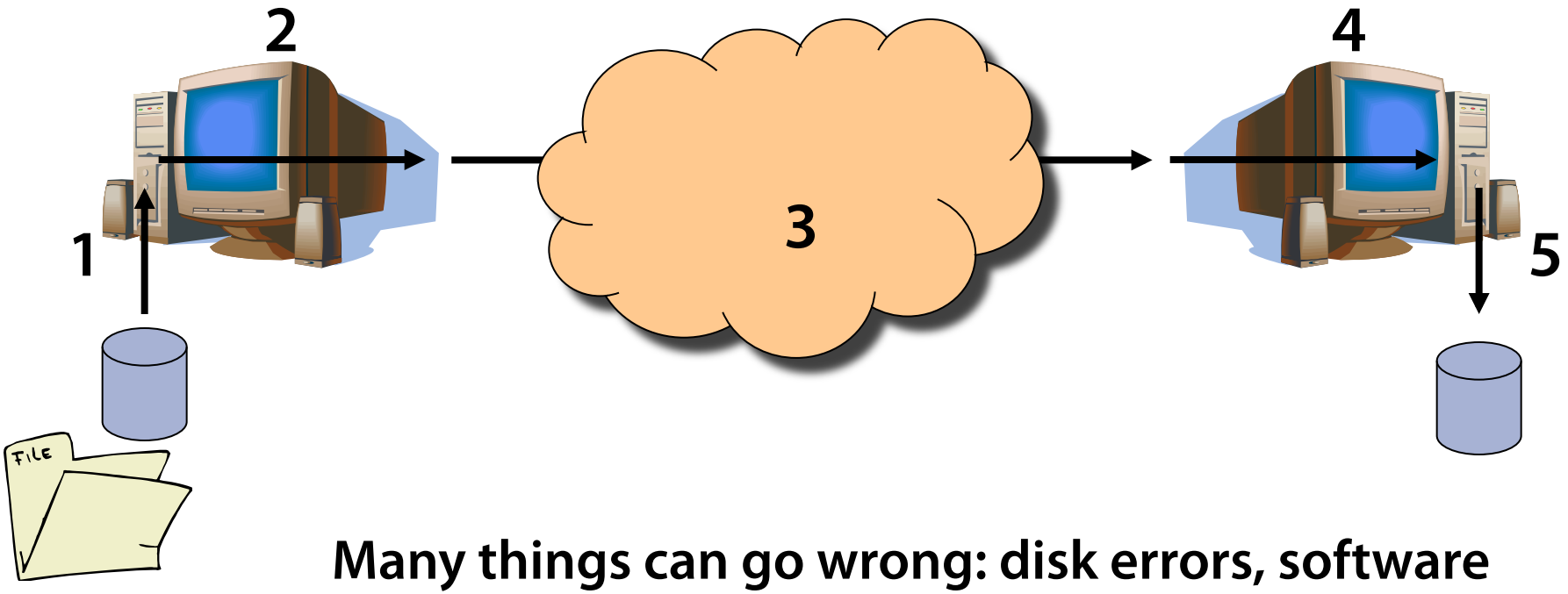
"End-to-End Arguments in System Design"

(*ACM Trans. on Computer Systems*, November 1984)

J. Saltzer, D. Reed, and D. Clark

End-to-End Argument

Operations should occur only at the end points
… unless needed for performance optimization



Many things can go wrong: disk errors, software errors, hardware errors, communication errors, …

Trade-Offs

Put functionality at each hop

- All applications pay the price
- End systems *still* need to check for errors

Place functionality only at the ends

- Slower error detection
- End-to-end retransmission wastes bandwidth

Compromise solution?

- Reliable end-to-end transport protocol (TCP)
- Plus file checksums to detect file-system errors

Discussion

When should the network support a function?

- What about link-layer retransmission in a wireless network?

Whose interests are served by the end-to-end argument?

How does a network operator influence the network without violating the end-to-end argument?

Does the design of IP and TCP make it *hard* to violate the end-to-end argument?

- For example: middleboxes like NATs, firewalls, proxies.

Should the end-to-end argument apply to routing?