CS162
Operating Systems and Systems Programming
Lecture 21

Layering, E2E Argument

April 12th, 2017

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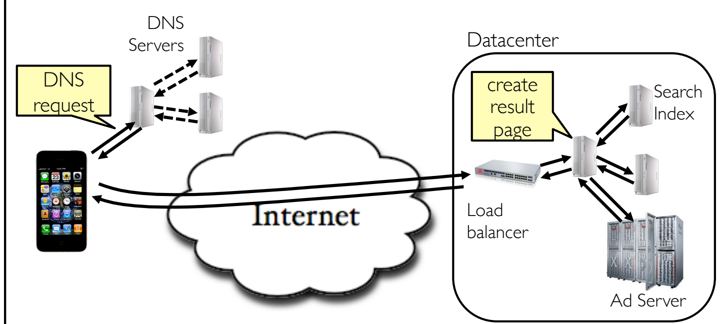
http://cs162.eecs.Berkeley.edu

Example: What's in a Search Query?



- Complex interaction of multiple components in multiple administrative domains

Goals for Today

- Layering
- End-to-end arguments

Some slides generated from Vern Paxson and Scott Shenker lecture notes

Why is Networking Important?

- Virtually all apps you use communicate over network
  - Many times main functionality is implemented remotely (e.g., Google services, Amazon, Facebook, Twitter, …)
- Thus, connectivity is key service provided by an OS
  - Many times, connectivity issues → among top complaints

Why is Networking Important?

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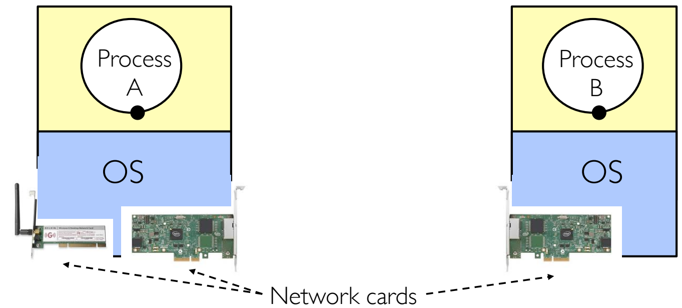
  - Many times main functionality is implemented remotely (e.g., Google services, Amazon, Facebook, Twitter, …)
- Thus, connectivity is key service provided by an OS
  - Many times, connectivity issues → among top complaints
- Some of the hottest opportunities in the OS space:
  - Optimize OS for network elements (e.g., intrusion detection, firewalls)
  - OSes for Software Defined Networks (SDNs)

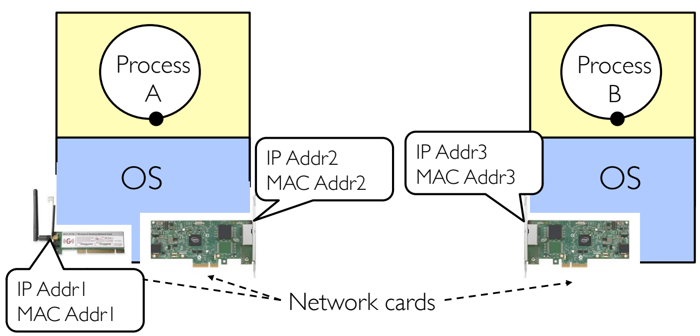
Network Concepts

- **Network (interface) card/controller**: hardware that physically connects a computer to the network
- A computer can have more than one networking cards
  - E.g., one card for wired network, and one for wireless network



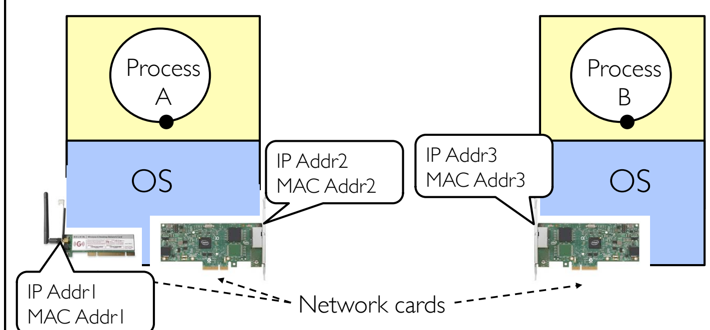
Network Concepts (cont'd)

- Typically, each network card is associated two addresses:
  - Media Access Control (MAC), or physical, address
  - IP, or network, address (can be shared by network cards on same host)



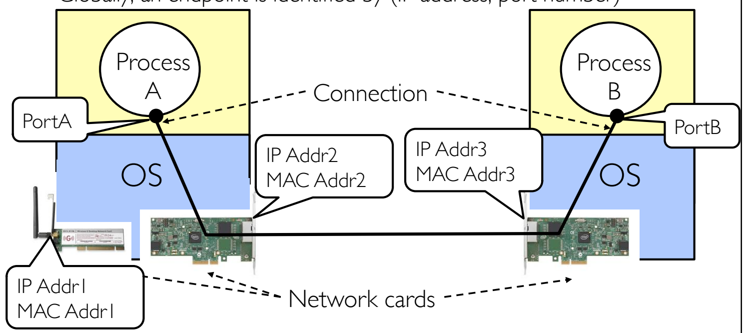
Network Concepts (cont'd)

- **MAC address**: 48-bit unique identifier assigned by card vendor
- **IP Address**: 32-bit (or 128-bit for IPv6) address assigned by network administrator or dynamically when computer connects to network



Network Concepts (cont'd)

- **Connection**: communication channel between two processes
- Each endpoint is identified by a **port number**
  - **Port number**: 16-bit identifier assigned by app or OS
  - Globally, an endpoint is identified by (IP address, port number)



Main Network Functionalities

- **Delivery**: deliver packets between any two hosts in the Internet
  - E.g., how do you deliver a packet from a host in Berkeley to a host in Tokyo?
- **Reliability**: tolerate packet losses
  - E.g., how do you ensure all bits of a file are delivered in the presence of packet loses?
- **Flow control**: avoid overflowing the receiver buffer
  - Recall our bounded buffer example: stop sender from overflowing buffer
  - E.g., how do you ensure that a sever that can send at 10Gbps doesn't overwhelm a 4G phone?
- **Congestion control**: avoid overflowing the buffer of a router along the path
  - What happens if we don't do it?

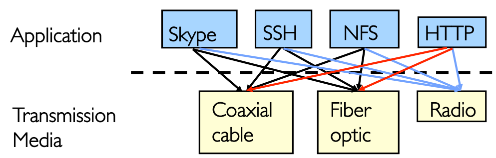
Protocol Standardization

- Ensure communicating hosts speak the same protocol
  - Standardization to enable multiple implementations
  - Or, the same folks have to write all the software
- Standardization: Internet Engineering Task Force
  - Based on working groups that focus on specific issues
  - Produces "Request For Comments" (RFCs)
    - » Promoted to standards via rough consensus and running code
  - IETF Web site is *http://www.ietf.org*
  - RFCs archived at *http://www.rfc-editor.org*
- De facto standards: same folks writing the code
  - P2P file sharing, Skype, <your protocol here>…

Layering: The Problem

- Many different applications
  - email, web, P2P, etc.
- Many different network styles and technologies
  - Circuit-switched vs packet-switched, etc.
  - Wireless vs. wired vs optical, etc.
- How do we organize this mess?

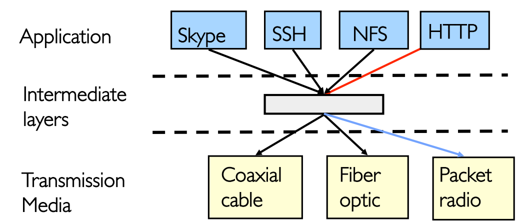
The Problem (cont'd)



- Re-implement every application for every technology?
- No! But how does the Internet design avoid this?

Solution: Intermediate Layers

- Introduce intermediate layers that provide set of abstractions for various network functionality & technologies
  - A new app/media implemented only once
  - Variation on "add another level of indirection"



Software System Modularity

Partition system into modules & abstractions:

- Well-defined interfaces give flexibility
  - *Hides* implementation - thus, it can be freely changed
  - Extend functionality of system by adding new modules
- E.g., libraries encapsulating set of functionality
- E.g., programming language + compiler abstracts away not only how the particular CPU works …
  - … but also the basic computational model
- Well-defined interfaces hide information
  - Isolate assumptions
  - Present high-level abstractions
  - But can impair performance

Network System Modularity

Like software modularity, but:

- Implementation distributed across many machines (routers and hosts)
- Must decide:
  - How to break system into modules
    - » Layering
  - What functionality does each module implement
    - » End-to-End Principle
  - Where state is stored
    - » Fate-sharing
- We will address these choices in turn

Layering: A Modular Approach

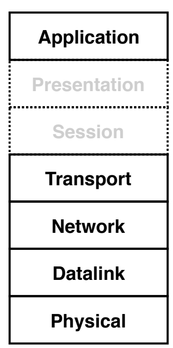
- Partition the system
  - Each layer solely relies on services from layer below
  - Each layer solely exports services to layer above
- Interface between layers defines interaction
  - Hides implementation details
  - Layers can change without disturbing other layers

Properties of Layers (OSI Model)

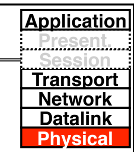
- Service: what a layer does
- Service interface: how to access the service
  - Interface for layer above
- Protocol (*peer interface*): how peers communicate to implement the service
  - Set of rules and formats that specify the communication between network elements
  - Does *not* specify the implementation on a single machine, but how the layer is implemented *between* machines

OSI Layering Model

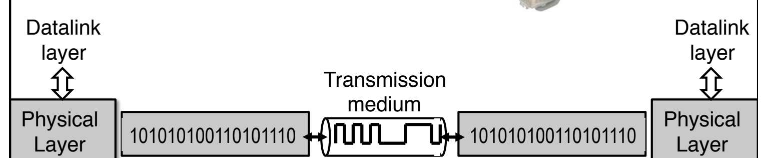
- Open Systems Interconnection (OSI) model
  - Developed by International Organization for Standardization (OSI) in 1984
  - Seven layers
- Internet Protocol (IP)
  - Only five layers
  - The functionalities of the missing layers (i.e., Presentation and Session) are provided by the Application layer



Physical Layer (1)



- Service: move information between two systems connected by a physical link
- Interface: specifies how to send and receive bits
- Protocol: coding scheme used to represent a bit, voltage levels, duration of a bit
- Examples: coaxial cable, optical fiber links; transmitters, receivers



Datalink Layer (2)

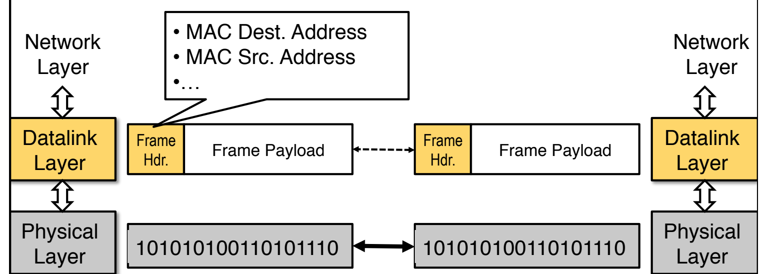
Application
Present.
Session
Transport
Network
Datalink
Physical

- Service:
  - Enable end hosts to exchange frames (atomic messages) on the same physical line or wireless link
  - Possible other services:
    - » Arbitrate access to common physical media
    - » May provide reliable transmission, flow control
- Interface: send *frames* to other end *hosts*; receive *frames* addressed to end host
- Protocols: addressing, Media Access Control (MAC) (e.g., CSMA/CD - *Carrier Sense Multiple Access / Collision Detection*)

Datalink Layer (2)

Application
Present.
Session
Transport
Network
Datalink
Physical

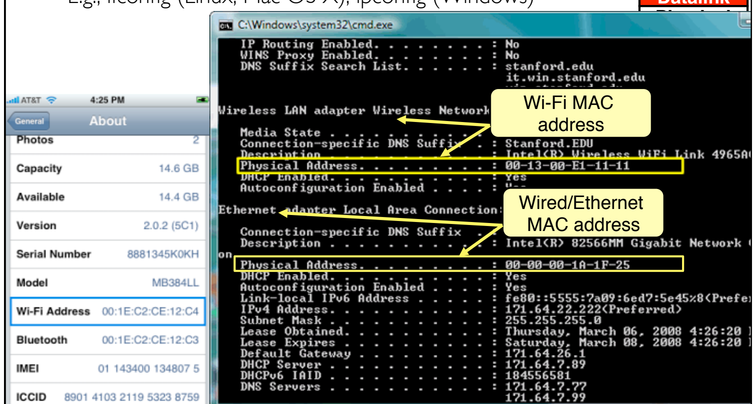
- Each frame has a header which contains a source and a destination MAC address
- MAC (Media Access Control) address
  - Uniquely identifies a network interface
  - 48-bit, assigned by the device manufacturer



MAC Address Examples

Application
Present.
Session
Transport
Network
Datalink

- Can easily find MAC addr. on your machine/device:
  - E.g., ifconfig (Linux, Mac OS X), ipconfig (Windows)



Local Area Networks (LANs)

Application
Present.
Session
Transport
Network
Datalink
Physical

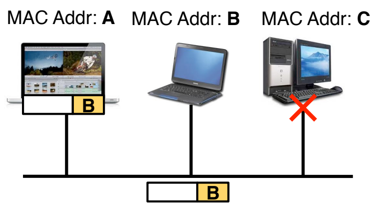
- LAN: group of hosts/devices that
  - are in the same geographical proximity (e.g., same building, room)
  - use same physical communication technology
- Examples:
  - all laptops connected wirelessly at a Starbucks café
  - all devices and computers at home
  - all hosts connected to wired Ethernet in an office

Ethernet cable and port

LANs

Application | Present. | Session | Transport | Network | **Datalink** | Physical

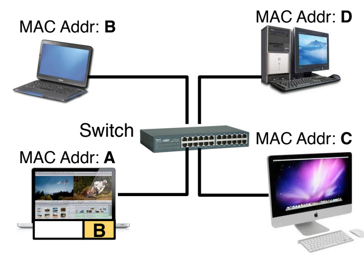
- All hosts in a LAN can share same physical communication media
  - Also called, broadcast channel
- Each frame is delivered to every host
- If a host is not the intended recipient, it drops the frame



Switches

Application | Present. | Session | Transport | Network | **Datalink** | Physical

- Hosts in same LAN can be also connected by switches
- A switch forwards frames only to intended recipients
  - Far more efficient than broadcast channel



Media Access Control (MAC) Protocols

Application | Present. | Session | Transport | Network | **Datalink** | Physical

- Problem:
  - How do hosts access a broadcast media?
  - How do they avoid collisions?
- Three solutions:
  - Channel partition
  - "Taking turns"
  - Random access

MAC Protocols

Application | Present. | Session | Transport | Network | **Datalink** | Physical

- Channel partitioning protocols:
  - Allocate 1/N bandwidth to every host
  - Share channel efficiently and fairly at high load
  - Inefficient at low load (where load = # senders):
    - » 1/N bandwidth allocated even if only 1 active node!
  - E.g., Frequency Division Multiple Access (FDMA); optical networks
- "Taking turns" protocols:
  - Pass a token around active hosts
  - A host can only send data if it has the token
  - More efficient at low loads: single node can use >> 1/N banwidth
  - Overhead in acquiring the token
  - Vulnerable to failures (e.g., failed node or lost token)
  - E.g., Token ring

MAC Protocols

Application
Present.
Session
Transport
Network
Datalink
Physical

- Random Access
  - Efficient at low load: single node can fully utilize channel
  - High load: collision overhead
- Key ideas of random access:
  - Carrier sense (CS)
    - » *Listen before speaking, and don't interrupt*
    - » Checking if someone else is already sending data
    - » … and waiting till the other node is done
  - Collision detection (CD)
    - » *If someone else starts talking at the same time, stop*
    - » Realizing when two nodes are transmitting at once
    - » …by detecting that the data on the wire is garbled
  - Randomness
    - » *Don't start talking again right away*
    - » Waiting for a random time before trying again
  - Examples: CSMA/CD, Ethernet, best known implementation

(Inter) Network Layer (3)

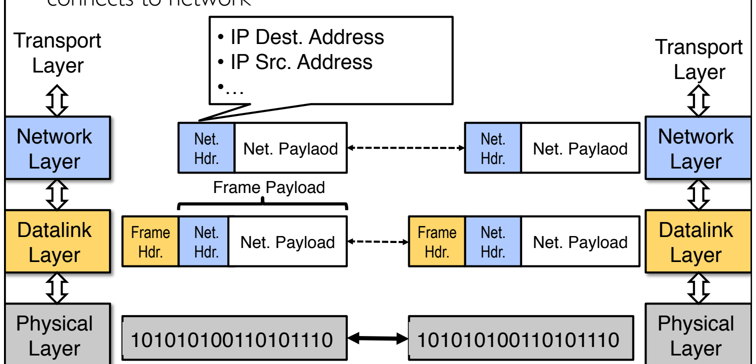
Application
Present.
Session
Transport
Network
Datalink
Physical

- Service:
  - Deliver packets to specified network addresses across multiple datalink layer networks
  - Possible other services:
    - » Packet *scheduling/priority*
    - » Buffer management
- Interface: send *packets* to specified network address destination; receive packets destined for end host
- Protocols: define network addresses (globally unique); construct forwarding tables; packet forwarding

(Inter) Network Layer (3)

Application
Present.
Session
Transport
Network
Datalink
Physical

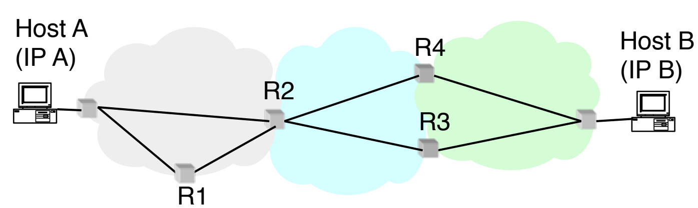
- IP address: unique addr. assigned to network device
- Assigned by network administrator or dynamically when host connects to network



Wide Area Network

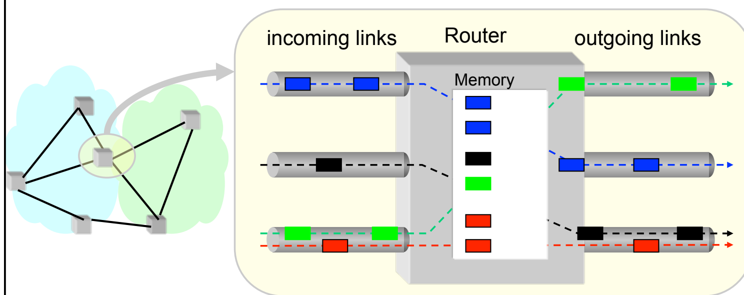
Application
Present.
Session
Transport
Network
Datalink
Physical

- Wide Area Network (WAN): network that covers a broad area (e.g., city, state, country, entire world)
  - E.g., Internet is a WAN
- WAN connects multiple datalink layer networks (LANs)
- Datalink layer networks are connected by routers
  - Different LANs can use different communication technology (e.g., wireless, cellular, optics, wired)



Routers

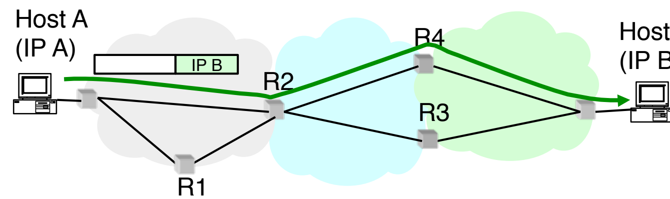
- **Forward** each packet received on an **incoming link** to an **outgoing link** based on packet's destination IP address (towards its destination)
- **Store & forward**: packets are buffered before being forwarded
- **Forwarding table**: mapping between IP address and the output link



Packet Forwarding

Application
Present.
Session
Transport
Network
Datalink
Physical

- Upon receiving a packet, a router
  - read the IP destination address of the packet
  - consults its forwarding table → output port
  - forwards packet to corresponding output port



IP Addresses vs. MAC Addresses

Application
Present.
Session
Transport
Network
Datalink
Physical

- Why not use MAC addresses for routing?
  - Doesn't scale
- Analogy
  - MAC address → SSN
  - IP address → (unreadable) home address
- MAC address: uniquely associated to the device for the entire lifetime of the device
- IP address: changes as the device location changes
  - Your notebook IP address at school is different from home

IP Addresses vs. MAC Addresses

Application
Present.
Session
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Network
Datalink
Physical

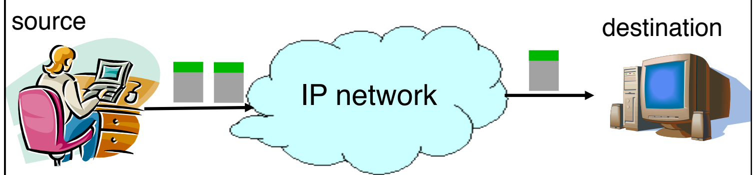
- Why does packet forwarding using IP addr. scale?
- Because IP addresses can be aggregated
  - E.g., all IP addresses at UC Berkeley start with **0xA9E5**, i.e., any address of form 0xA9E5**** belongs to Berkeley
  - Thus, a router in NY needs to keep a **single** entry for **all** hosts at Berkeley
  - If we were using MAC addresses the NY router would need to maintain **an entry for every** Berkeley host!!

- Analogy:
  - Give this letter to person with SSN: 123-45-6789 vs.
  - Give this letter to "John Smith, 123 First Street, LA, US"

The Internet Protocol (IP)

Application
Present.
Session
Transport
Network
Datalink
Physical

- Internet Protocol: Internet' s network layer
- Service it provides: "Best-Effort" Packet Delivery
  - Tries it' s "best" to deliver packet to its destination
  - Packets may be lost
  - Packets may be corrupted
  - Packets may be delivered out of order



Transport Layer (4)

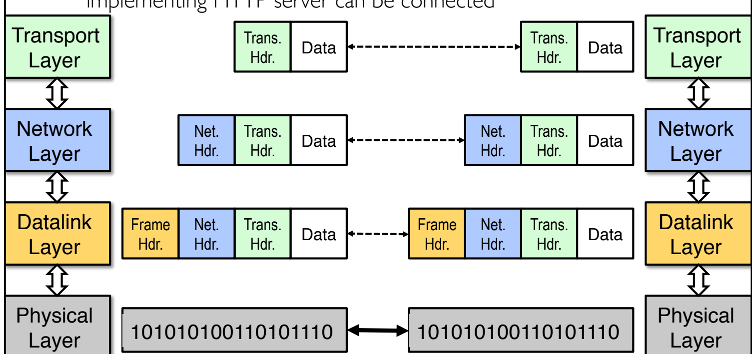
Application
Present.
Session
Transport
Network
Datalink
Physical

- Service:
  - Provide end-to-end communication between processes
  - Demultiplexing of communication between hosts
  - Possible other services:
    - » Reliability in the presence of errors
    - » Timing properties
    - » Rate adaption (flow-control, congestion control)
- Interface: send message to specific process at given destination; local process receives messages sent to it
- Protocol: port numbers, perhaps implement reliability, flow control, packetization of large messages, framing
- Examples: TCP and UDP

Port Numbers

Application
Present.
Session
Transport
Network
Datalink
Physical

- Port number: 16-bit number identifying the end-point of a transport connection
  - E.g., 80 identifies the port on which a processing implementing HTTP server can be connected

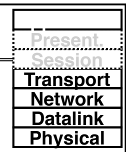


Internet Transport Protocols

Application
Present.
Session
Transport
Network
Datalink
Physical

- Datagram service (UDP)
  - No-frills extension of "best-effort" IP
  - Multiplexing/Demultiplexing among processes
- Reliable, in-order delivery (TCP)
  - Connection set-up & tear-down
  - Discarding corrupted packets (segments)
  - Retransmission of lost packets (segments)
  - Flow control
  - Congestion control
- Services not available
  - Delay and/or bandwidth guarantees
  - Sessions that survive change-of-IP-address

Application Layer (7 - not 5!)

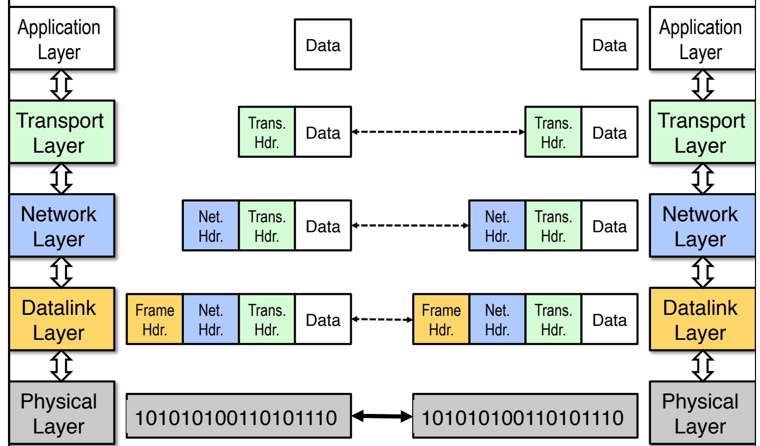


- Service: any service provided to the end user
- Interface: depends on the application
- Protocol: depends on the application

- Examples: Skype, SMTP (email), HTTP (Web), Halo, BitTorrent …

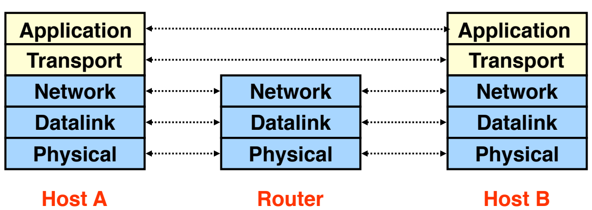
- What happened to layers 5 & 6?
  - “Session” and “Presentation” layers
  - Part of *OSI* architecture, but not Internet architecture
  - Their functionality is provided by application layer

Application Layer (5)



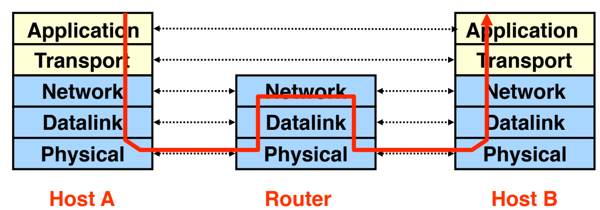
Five Layers Summary

- Lower three layers implemented everywhere
- Top two layers implemented only at hosts
- Logically, layers interacts with peer’s corresponding layer



Physical Communication

- Communication goes down to physical network
- Then from network peer to peer
- Then up to relevant layer

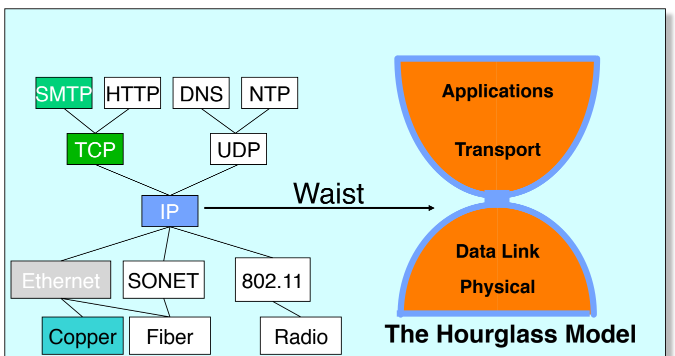


Administrivia

- Midterm 3 coming up on **Mon 4/24 6:30-8PM**
  - All topics up to and including Lecture 15
    - » Focus will be on Lectures 16 – 23 and associated readings, and Projects 3
    - » But expect 20-30% questions from materials from Lectures 1-15
  - VLSB 2040 and VLSB 2060
  - Closed book
  - 2 pages hand-written notes both sides

BREAK

The Internet *Hourglass*



There is just one network-layer protocol, IP.
The "narrow waist" facilitates interoperability.

Implications of Hourglass

Single Internet-layer module (IP):

- Allows arbitrary networks to interoperate
  - Any network technology that supports IP can exchange packets
- Allows applications to function on all networks
  - Applications that can run on IP can use any network
- Supports simultaneous innovations above and below IP
  - But changing IP itself, i.e., IPv6, very involved

Drawbacks of Layering

- Layer N may duplicate layer N-1 functionality
  - E.g., error recovery to retransmit lost data
- Layers may need same information
  - E.g., timestamps, maximum transmission unit size
- Layering can hurt performance
  - E.g., hiding details about what is really going on
- Some layers are not always cleanly separated
  - Inter-layer dependencies for performance reasons
  - Some dependencies in standards (header checksums)
- Headers start to get really big
  - Sometimes header bytes >> actual content

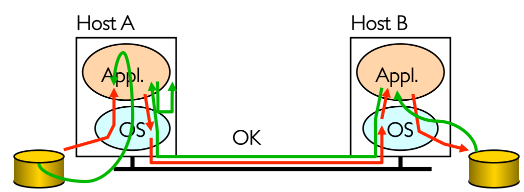
Placing Network Functionality

- Hugely influential paper: "End-to-End Arguments in System Design" by Saltzer, Reed, and Clark ('84)
- "Sacred Text" of the Internet
  - Endless disputes about what it means
  - Everyone cites it as supporting their position

Basic Observation

- Some types of network functionality can only be correctly implemented end-to-end
  - Reliability, security, etc
- Because of this, end hosts:
  - Can satisfy the requirement without network's help
  - Will/**must** do so, since can't *rely* on network's help
- Therefore **don't** go out of your way to implement them in the network

Example: Reliable File Transfer



- Solution 1: make each step reliable, and then concatenate them
- Solution 2: end-to-end **check** and try again if necessary

Discussion

- Solution 1 is incomplete
  - What happens if memory is corrupted?
  - Receiver has to do the check anyway!
- Solution 2 is complete
  - Full functionality can be entirely implemented at application layer with no need for reliability from lower layers
- *Is there any need to implement reliability at lower layers?*
  - Well, it could be more efficient

End-to-End Principle

Implementing this functionality in the network:

- Doesn't reduce host implementation complexity
- Does increase network complexity
- Probably imposes delay and overhead on all applications, even if they don't need functionality
- However, implementing in network can enhance performance in some cases
  - E.g., very lossy link

Conservative Interpretation of E2E

- Don't implement a function at the lower levels of the system unless it can be completely implemented at this level
- Unless you can relieve the burden from hosts, don't bother

Moderate Interpretation

- Think twice before implementing functionality in the network
- If hosts can implement functionality correctly, implement it in a lower layer only as a performance enhancement
- But do so only if it does not impose burden on applications that do not require that functionality
- This is the interpretation we are using

Summary (1/2)

- Layered architecture powerful abstraction for organizing complex networks
- Internet: 5 layers
  - Physical: send bits
  - Datalink: Connect two hosts on same physical media
  - Network: Connect two hosts in a wide area network
  - Transport: Connect two processes on (remote) hosts
  - Applications: Enable applications running on remote hosts to interact
- Unified Internet layering (Application/Transport/ Internetwork/ Link/Physical) decouples apps from networking technologies

Summary (2/2)

- E2E argument encourages us to keep IP simple
- If higher layer can implement functionality correctly, implement it in a lower layer only if
  - it improves the performance significantly for application that need that functionality, and
  - it does not impose burden on applications that do not require that functionality