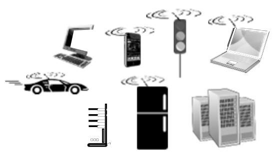
Architectures, Layers, and Standards #3

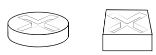
Outline

- Physical Architecture
- Network Architecture
- Network Standards
- Layering and Protocol Stacks

Physical Architecture

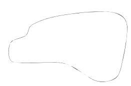


Billions of connected computing *devices*:
- *hosts = end systems*
- running *network apps* at Internet's "edge"

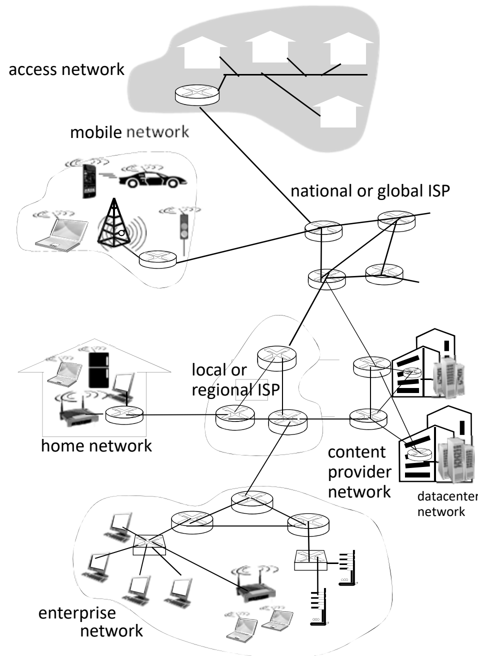


Packet switches: forward packets (chunks of data)
- *routers*, *switches*

Communication links
- fiber, copper, radio, satellite
- transmission rate: *bandwidth*

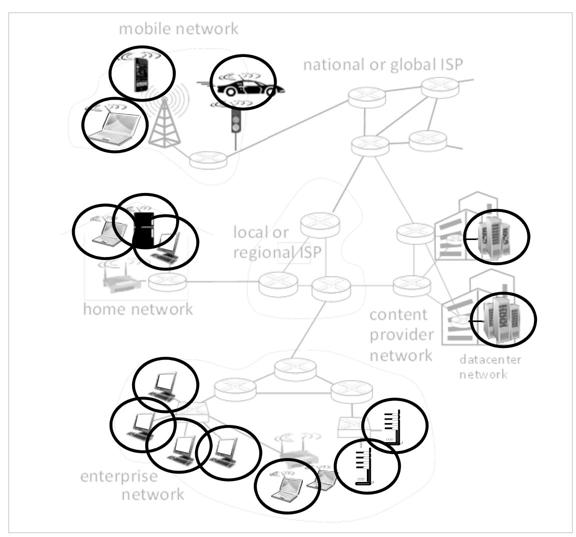


Networks
- collection of devices, routers, links: managed by an organization



Network core and edge

Network edge:
- hosts: clients and servers
- servers often in data centers



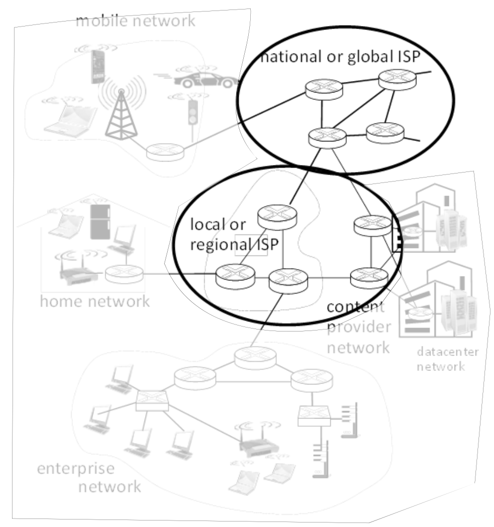
Network core and edge

Network edge:

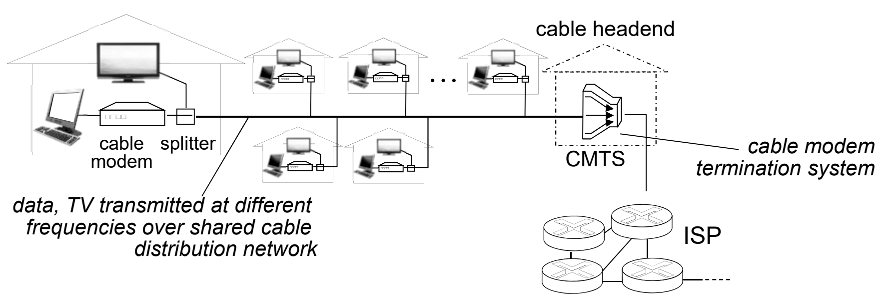
- hosts: clients and servers
- servers often in data centers

Network core:

- interconnected routers
- network of networks

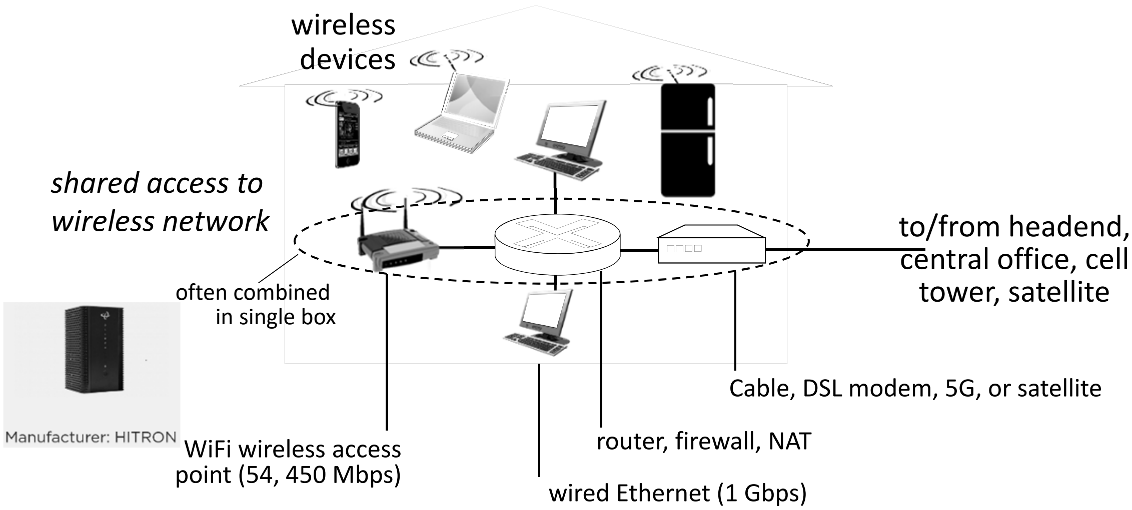


Access networks: cable-based access



- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbs downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend

Access networks: home networks



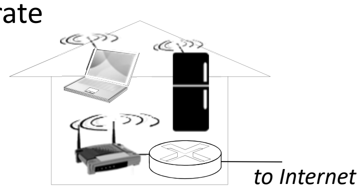
Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka "access point"

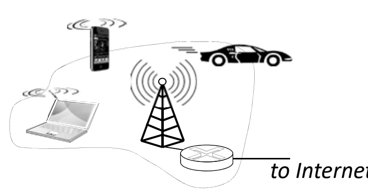
Wireless local area networks (WLANs)

- typically within or around building (~100 ft)
- 802.11b/g/n/ac/ax (WiFi): 11, 54, 450 Mbps, to Gb/s transmission rate

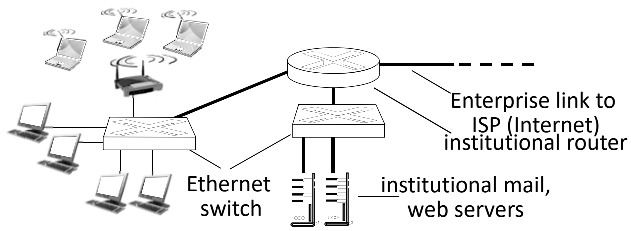


Wide-area cellular access networks

- provided by mobile, cellular network operator (10's km)
- 10's-100's Mbps
- 4G & 5G cellular networks

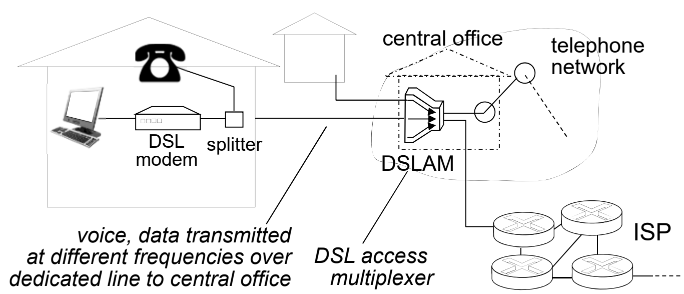


Access networks: enterprise networks



- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover later)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

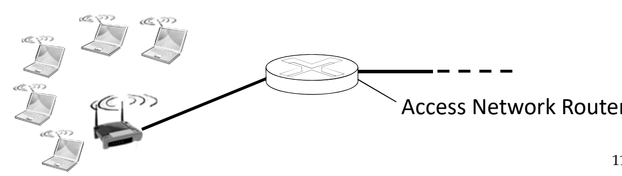
Access networks: digital subscriber line (DSL)



- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - access not over shared facility
  - voice over DSL phone line goes to telephone net
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

Comments on access networks

- End devices directly connected to access network
- All devices have an access network identifier, address
  - Media Access Control (MAC)-Ethernet & WiFi
  - Layer 2 Address
  - International Mobile Equipment Identity (IMEI) number-smart phones
- Once a packet from the outside reaches the access network, the access network can directly deliver the packet to end device
  - A broadcast network has this property
  - Some access networks are naturally broadcast, e.g., wireless LANs
  - Some access networks are virtually broadcast, e.g., switched LANs
- End Result: <u>the goal of the external network is to deliver the packet to the access network, the access network then directly deliver the packet to end device.</u>

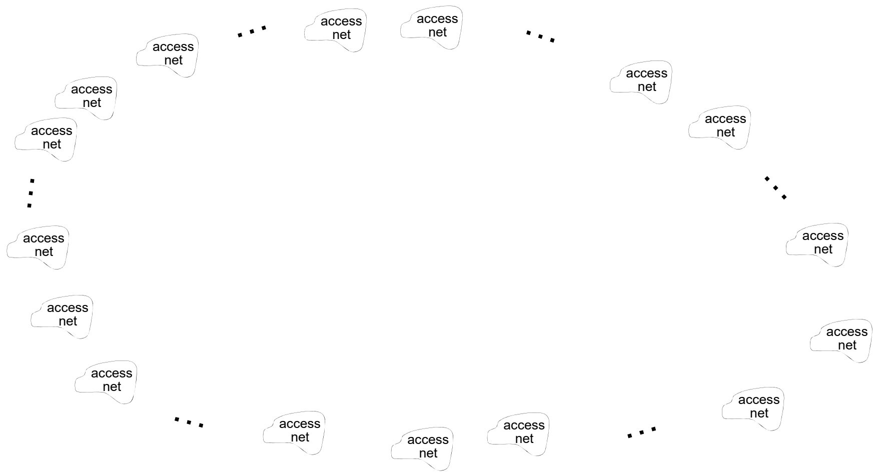


Internet structure: a "network of networks"

- Hosts connect to Internet via access Internet Service Providers (ISPs)
  - residential, enterprise (company, university, commercial) ISPs
- Access ISPs in turn must be interconnected
  - so that any two hosts can send packets to each other
- Resulting network of networks is very complex
  - evolution was driven by economics and national policies
- Let's take a stepwise approach to describe current Internet structure

Internet structure: a "network of networks"

Question: given *millions* of access ISPs, how to connect them together?



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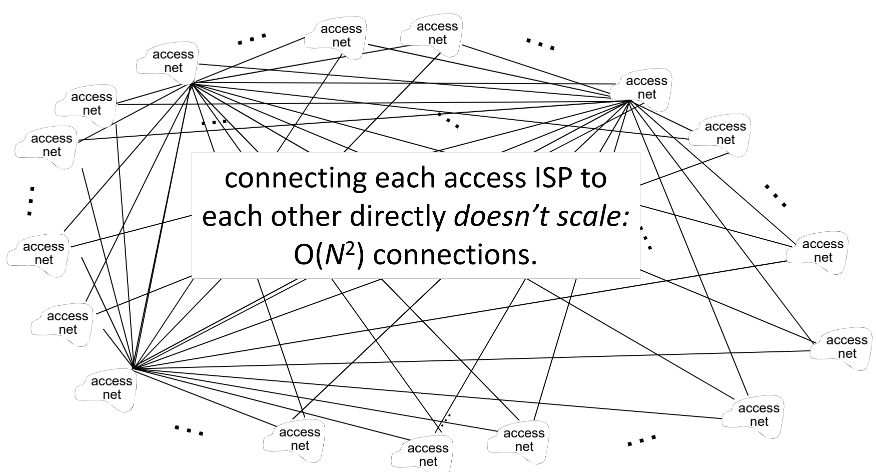
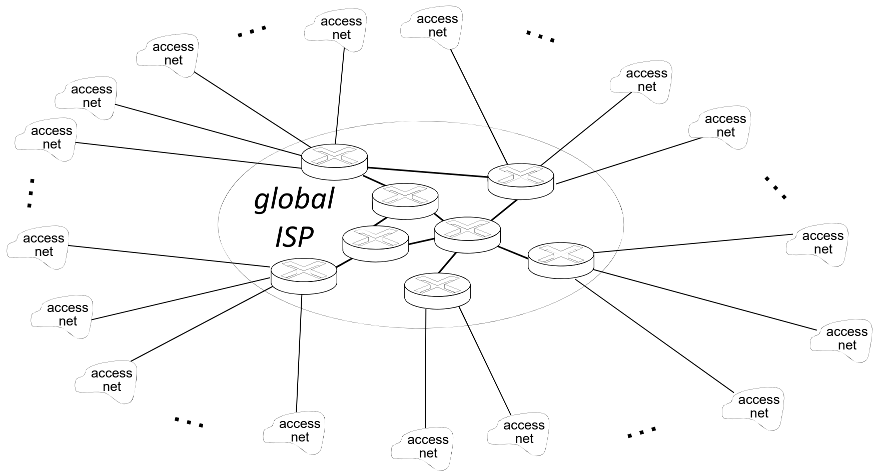


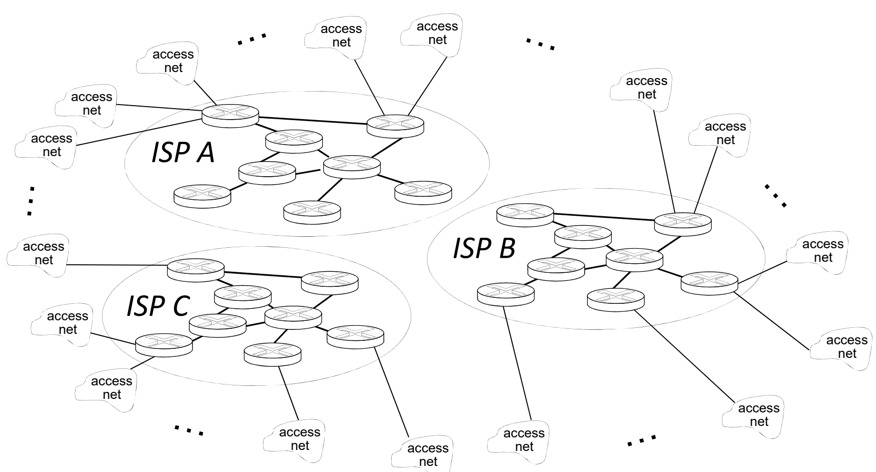
Internet structure: a "network of networks"

Option: connect each access ISP to one global transit ISP?
Customer and provider ISPs have economic agreement.



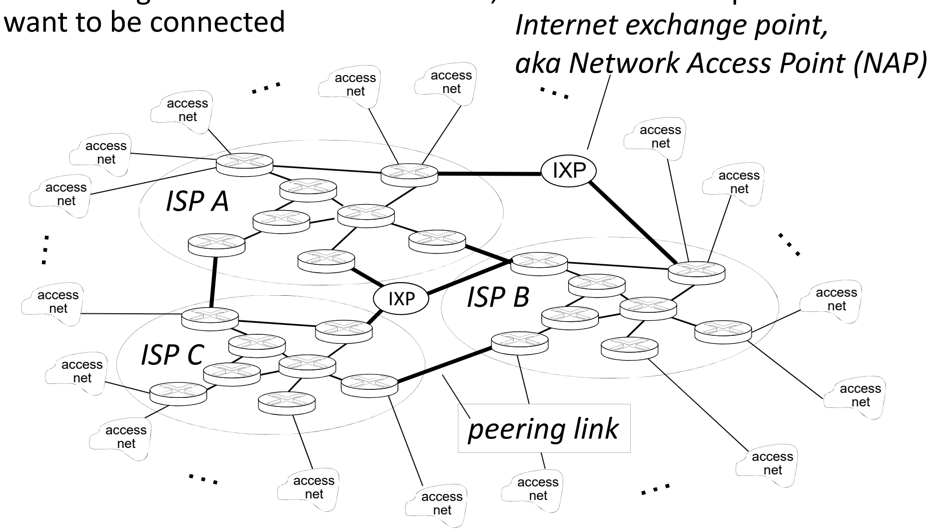
Internet structure: a "network of networks"

But if one global ISP is viable business, there will be competitors ….



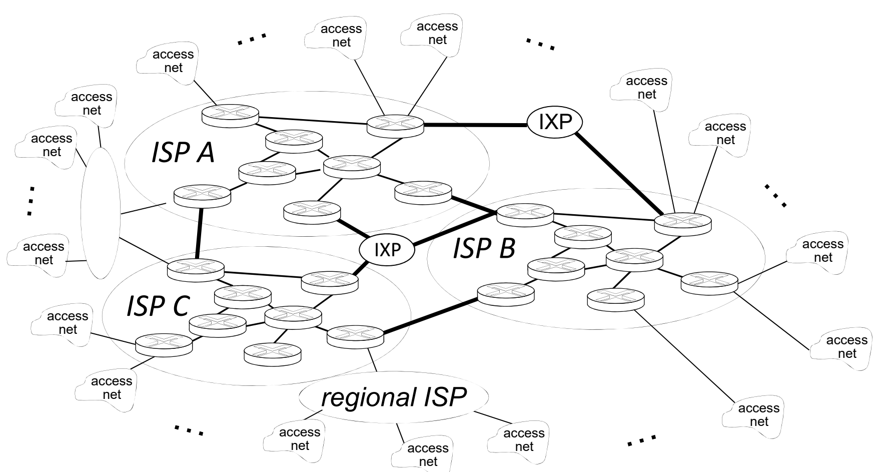
Internet structure: a “network of networks”

But if one global ISP is viable business, there will be competitors …. who will want to be connected



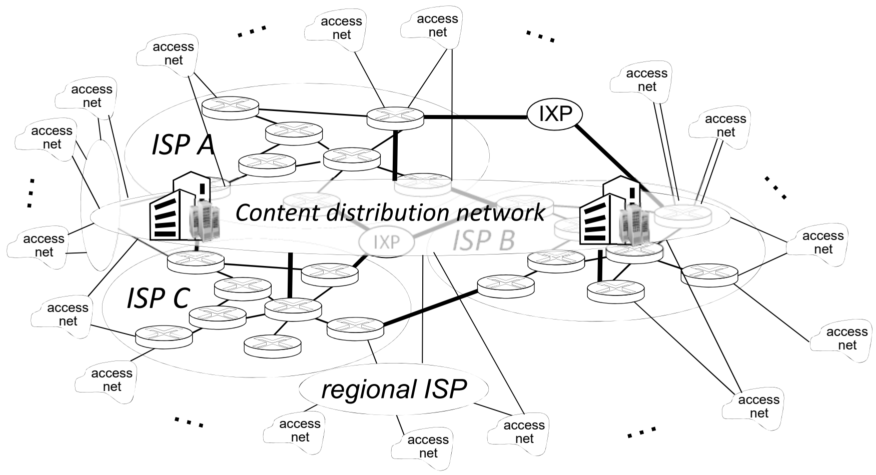
Internet structure: a “network of networks”

… and regional networks may arise to connect access nets to ISPs



Internet structure: a "network of networks"

… and content provider networks (e.g., Google, Microsoft, Akamai) may run their own network, to bring services, content close to end users



Modified from: 8th edition Jim Kurose, Keith Ross Pearson, 2020

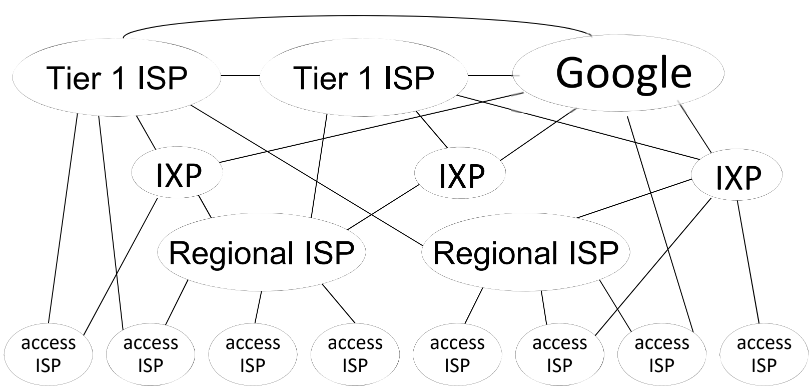
Content distribution networks (CDNs)

- A Content Distribution Network (CDN) is a system of distributed servers that work together to deliver web content, such as images, videos, stylesheets, scripts, and other static files, to users based on their geographical location.
- Purpose: to improve the performance, reliability, and availability of websites by reducing the latency and load times of web pages.
- CDN's provide website owners can enhance the overall user experience, reduce server load, and improve the speed and availability of their web content.
- Examples CDN providers: Cloudflare, Akamai, and Amazon CloudFront.

Content distribution networks (CDNs)

- Functions:
  - Content Replication: replicates and stores copies of the static content on multiple servers located at various data centers around the world.
  - Geographical Distribution: servers are strategically placed in different geographical locations to ensure that users can access content from a server that is physically closer to them. This reduces the time it takes for the content to travel from the server to the user, resulting in faster loading times.
  - Load Balancing: use load balancing techniques to distribute incoming traffic across multiple servers. This helps prevent any single server from becoming overwhelmed with too much traffic and ensures a more even distribution of the load.
  - Caching: employ caching mechanisms to store frequently accessed content closer to the end-users. When a user requests a specific piece of content, the CDN serves it from the nearest cached copy rather than fetching it from the origin server each time.

Internet structure: a "network of networks"



Example:
Access ISP
- Midco
- KU

At "center": small # of well-connected large networks

- "tier-1" commercial ISPs (e.g., Level 3, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

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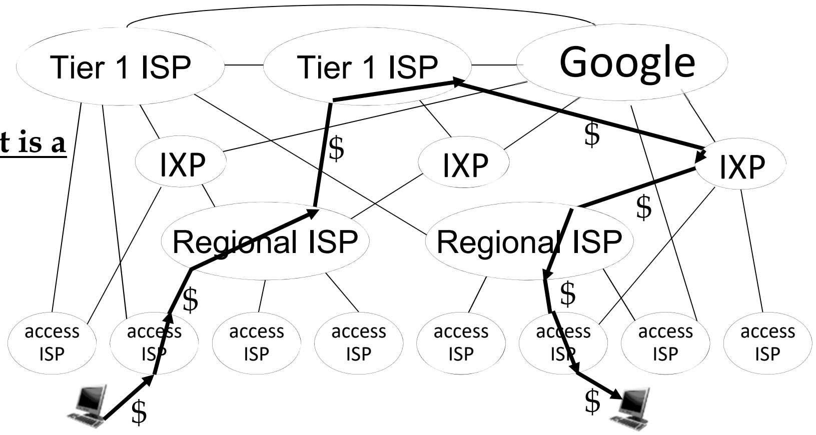
Internet structure: a “network of networks”



The Internet is a network of networks

At “center”: small # of well-connected large networks

- “tier-1” commercial ISPs (e.g., Level 3, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

Internet structure: network of networks

- How do you make it all work given:
  - Hardware from different vendors
  - Software from different vendors
  - Different computer/smartphone operating systems
  - Rapid change in enabling technologies, more:
    - CPU power
    - Memory
    - Link Capacity
    - New radios
  - Rapid introduction of new applications
  - Traffic transverses networks with different owners

Network Standards and Open Systems: <u>Need for Standards</u>

- Enable interoperability of equipment/software from different vendors
- Facilitate the building of a large market to reduce prices
- Standards lead to **<u>"Open Systems"</u>**
- With open systems customers are not locked into one vendor's solution
- Open systems lead to a <u>*"seamless"*</u> user environment, e.g., www

Network Standards and Open Systems: <u>Objectives for Standards</u>

- Standards process:
  - Development
  - Establishment
  - Promulgation
- Co-ordinate activity
- Assure consensus
- Information focal point
- Mechanism for management
  - Why do standards need to be managed?

Network Standards and Open Systems: <u>Standards Organizations</u>

- American National Standards Institute (ANSI)
  - Manufacturers
  - Organizations
  - Government
  - Users
- **<u>Internet Engineering Task Force (IETF)</u>**
  - Request for Comment (**<u>RFC</u>**)
- Electronic Industries Association (EIA)
  - Electronic manufacturers
- <u>International Telecommunications Union </u>(**ITU**) [Formerly: Consultative Committee International Telegraph Telephone CCITT]
  - National PTT's
  - Scientific organizations
  - Specialized agency of the United Nations
- **<u>IEEE,</u>** e.g. IEEE 802.11

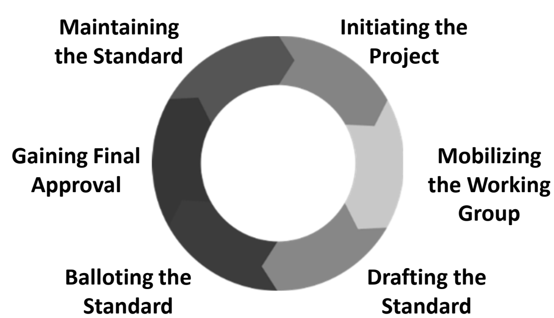
IEEE Standards Association

IEEE Standards drive the functionality, capability, and interoperability of a range of products and services that affect the way people live, work, and communicate.

Individual membership
6,879 individual members in 90 countries

Corporate Memberships
187 member corporations in 23 countries

Standards Developers
~20,000 participants;
all interested parties are welcome



From: IEEE 802.11 Overview and Completed Amendments, June 2022

Network Standards and Open Systems: Problems with Standards

- Freezes technology
- Multiple standards evolve for same system
- Standards take a long time to be established
- Difficult to evolve to meet rapidly changing needs
- Often standards are complex
- De-facto standards often emerge

Network Architectures

- "Architecture is about organization of functionality not its implementation" from [1]
- Standards require description and organization of network functionality
- Layered Architecture is the *"structuring"* of network functions
- Layered Architecture provides the *"modularity"* of network functions
- Modules/Layers break-up the functionality into smaller tasks
- Modules/Layers require clean interfaces.
- Note that implementations of network protocols require real-time distributed processing

[1] Extracting the Essential Simplicity of the Internet, By James Mccauley, Scott Shenker, George Varghese, Communications of the ACM, February 2023, Vol. 66 No. 2, Pages 64-74

Network Architectures and Reference Models

- Reference models provide:
  - A conceptual framework to characterize networks
  - A mechanism to control/describe the complexity of networks
  - Required for open systems

Network Architectures and Reference Models

- Layered Architectures must have
  - Structure
  - Symmetry
  - Peer protocols
- Structure is the collection of related processing functions into layers
- Symmetry requires compatible functions exist is source/destination systems
- Peer Protocols are the set of rules that govern the processing between peer entities, i.e., the source/destination

Network architectures:
Underlying Principles

- Minimize the number of layers thus simplifying the tasks of describing and integrating different layers.
- Establish boundaries at points where the description of services is small and the number of interactions is minimum.
- Create layers that include different functions.

Network architectures:
Underlying Principles

- Establish boundaries where history demonstrates that the implementation can be partitioned.
- Engineer layers so that they can could be redesigned to take advantage of new technology without changing the services and interfaces of adjacent layers.
- Allow for the bypassing of sublayers.
- Each layer should add value.

Example: Sending a package via Fedx

Insert into Fedx box	Remove from Fedx box
Take to Fedx Office	Pick up from FedX office
Deliver to regional office	Deliver to regional office
Put on airplane	Take off airplane
Airplane routing	Airplane routing

airplane routing

Package delivery: a series of steps, involving many services

Example: Organization of Fedx Delivery

Insert into FedX box	*Packing service*	Remove from Fedx box
Take to Fedx Office	*transport service*	Pick up from FedX office
Deliver to regional office	*consolidation service*	Deliver to regional office
Put on airplane	*runway service*	Take off airplane
Airplane routing	*routing service*	Airplane routing

layers: each layer implements a service

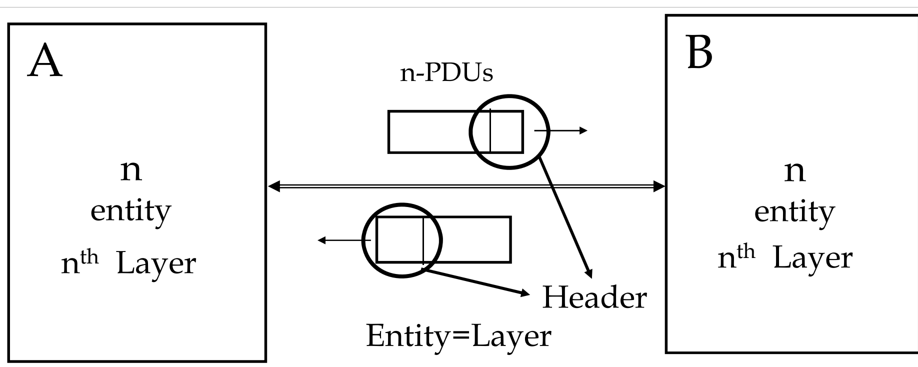
- via its own internal-layer actions
- relying on services provided by layer below

Why layering?

dealing with complex systems:

- Explicit structure allows identification, relationship of complex system's pieces
  - layered *reference model* for discussion
- Modularization eases maintenance, updating of system
  - change in layer's service *implementation*: transparent to rest of system
  - e.g., change input on airplane procedure does not affect rest of system
- Each layer adds "information" e.g., a header, to support processing packets at that layer.
- Protocols are partially described by defining the header information, e.g., the meaning of specific bits in the header.

Conceptual View of a Layer



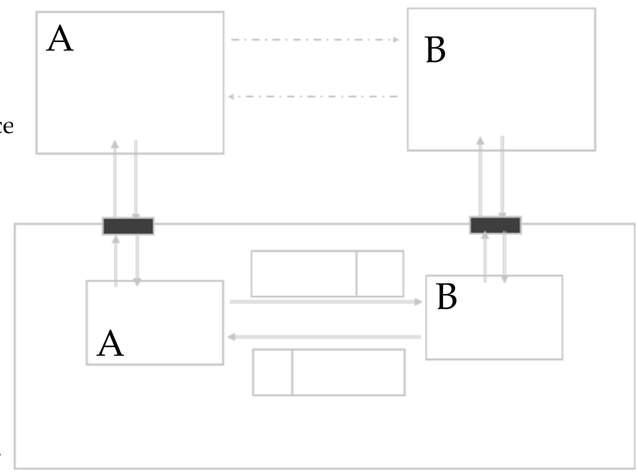
PDU stands for Protocol Data Unit,
which is the data unit that is created at each layer of the network stack.

Conceptual View of a Layer

- Service Data Units (SDU) is the data is passed down from the higher layers to the lower layers of the network stack

- Service Access Point (SAP) is the interface between these layers and allows them to communicate with each other by defining the format and structure of the data being exchanged.

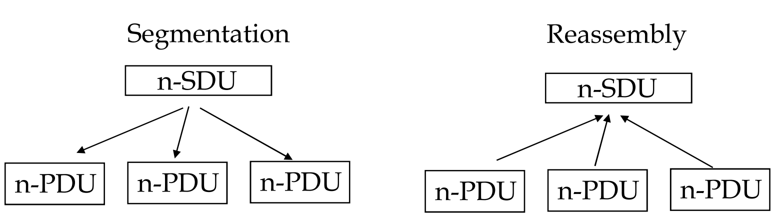
Each layer encapsulates the SDU into a PDU by adding a header and/or a trailer to the data, and passes it down to the next lower layer. The PDU of one layer becomes the SDU of the next lower layer.



Modified from: Leon-Garcia & Widjaja: *Communication Networks*

Conceptual View of a Layer

SDU arriving at an layer may be broken up into smaller PDUs.
Segmentation is the process of dividing a large data packet into smaller segments that can be transmitted over the network. The purpose of segmentation is to enable efficient transmission of data over the network by breaking up large packets into smaller, more manageable pieces. When a packet is segmented, each segment is assigned a unique sequence number, which is used to reassemble the packet at the destination.



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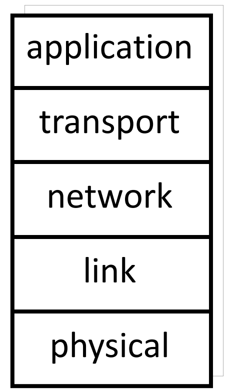
Internet protocol stack

- *application:* supporting network applications
  - E-mail (SMTP), www (HTTP)
- *transport:* process-process data transfer
  - TCP, UDP, RTP, more….
  - Host-to-host
- *network:* routing of datagrams from source to destination
  - IPv4, IPv6, routing protocols
- *link:* data transfer between neighboring network elements
  - Ethernet, 802.11 (WiFi), Point-to-Point Protocol (PPP)
- *physical:* bits "on the wire"



Layered Architecture: Internet

- Physical (PHY) layer (Layer 1)
  - Electrical/optical/radio connections-modulation formats
  - Mechanical connections
  - Functional Requirements
  - Procedural protocol
  - Bit transmission

How many PHY interfaces are on your smartphone?

Layered Architecture: Internet

- Link Layer (Layer 2)
  - Point-to-point (physical or virtual) connection
  - Interaction between end-systems and network
  - Makes higher layer software "independent" of underlying networking technology
  - Message Units at Layer 2 are typically called Frames
  - Some link-layer protocols provide reliable delivery of frames.

Layered Architecture: Internet

- Network Layer (Layer 3)
  - **<u>Routing</u>** between networks
  - Forwarding
  - Implemented in end systems
  - Implemented in routers
  - Internet Protocols
  - IP Message Units (Layer 3) are typically called Datagrams

Layered Architecture: Internet

- Transport Layer (Layer 4)
  - Implemented end-to-end
  - Services
    - Reliable end-to end- transport
      - Transport Control Protocol (TCP)
      - TCP message units are typically called Segments
      - Reliability is provided end-to-end
    - User datagram protocol (UDP)
      - No end-to-end reliability
    - Transport message units are typically called Segments

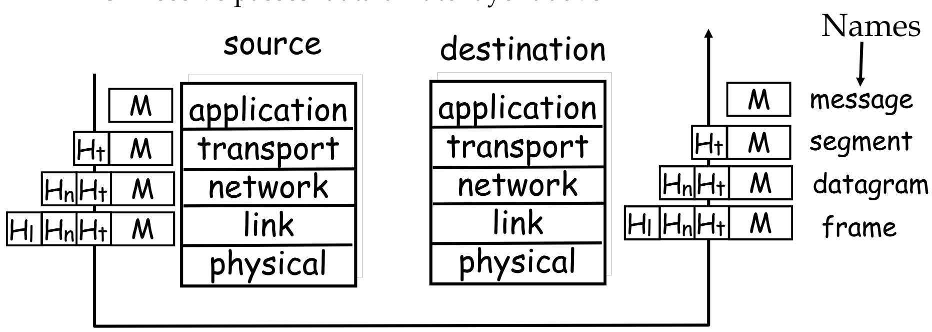
Layered Architecture: Internet

- Application Layer (Layer 5)
  - Mail
  - www
  - User created…..
  - Message units at the application layer are typically called Messages

Protocol layering and data

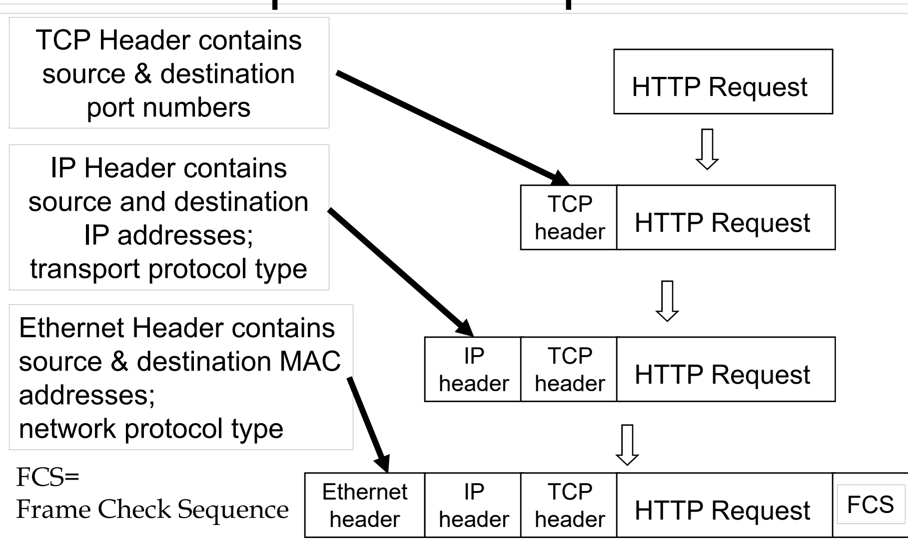
Each layer takes data from above

- Adds header information to create new data unit, H_{Layer}
- On transmission passes new data unit to layer below
- On receive passes data unit to layer above



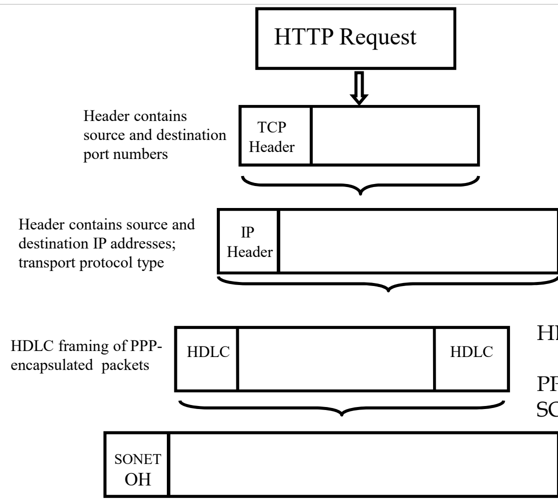
Modified from: *Computer Networking: A Top Down Approach Featuring the Internet,* 2nd edition. Jim Kurose, Keith Ross Addison-Wesley, July 2002.

Example of Encapsulation

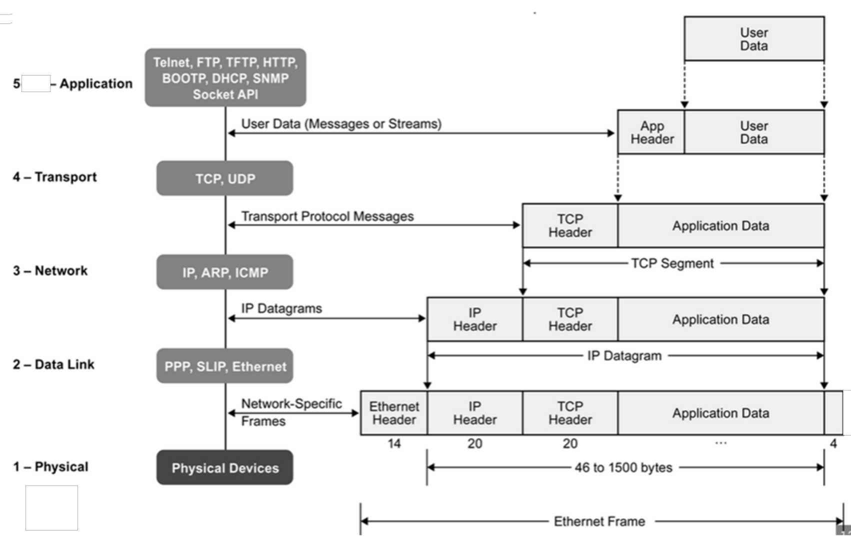


FCS=
Frame Check Sequence

Another Example of Encapsulation:
IP over Synchronous Optical Network (SONET)

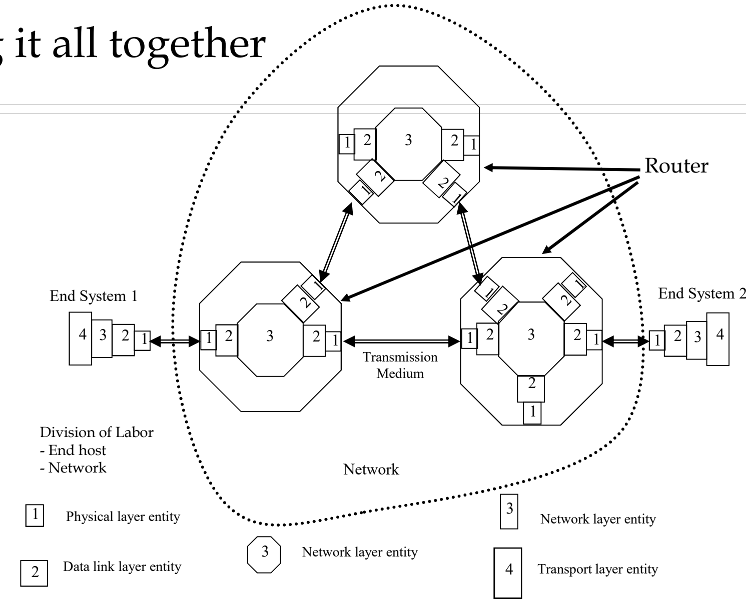


HDLC = High-Level Data Link Control
PPP = Point-to-Point Protocol
SONET = Synchronous Optical Network



Modified From: https://www.ssla.co.uk/protocol-stack-developer/

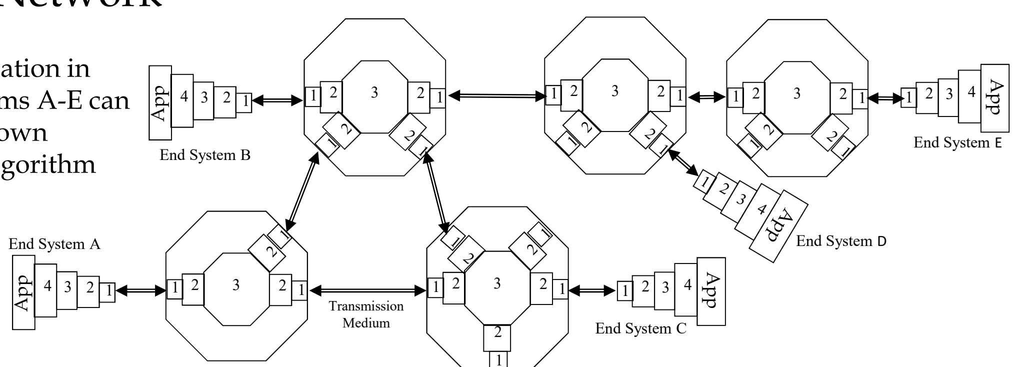
Putting it all together



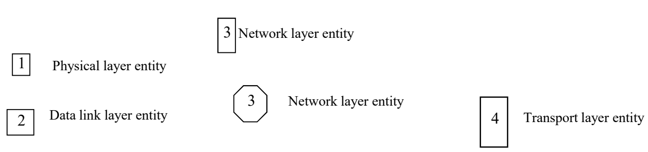
Modified from: Leon-Garcia & Widjaja: *Communication Networks*

Overlay Network

An application in end systems A-E can run their own routing algorithm



Idea behind "onion routing"
Onion routing enables anonymous communication over a computer network.
Tor is a privacy-focused network designed to enhance users' anonymity on the internet by routing their traffic through a series of volunteer-operated servers (i.e., end systems). Tor aims to provide a high level of privacy and security by obscuring the user's identity and location.
The Onion Router=Tor https://www.torproject.org/



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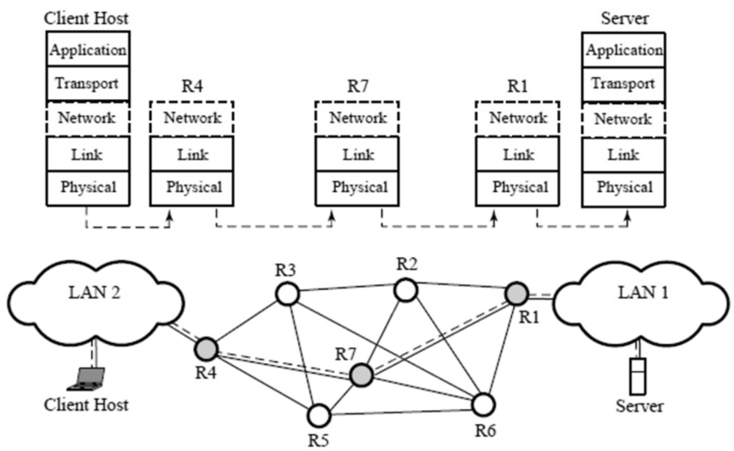
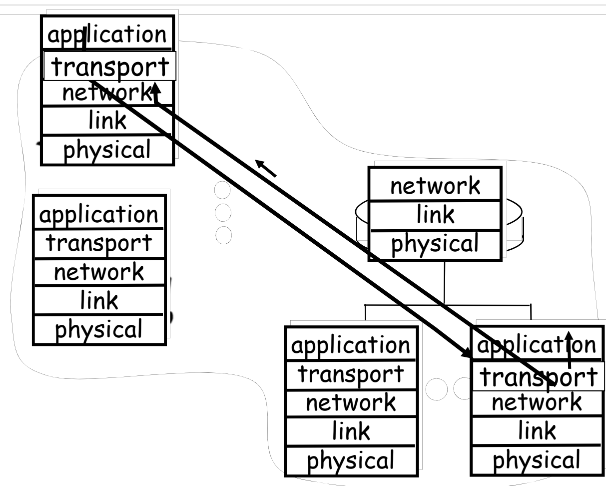


Layering: *logical* communication

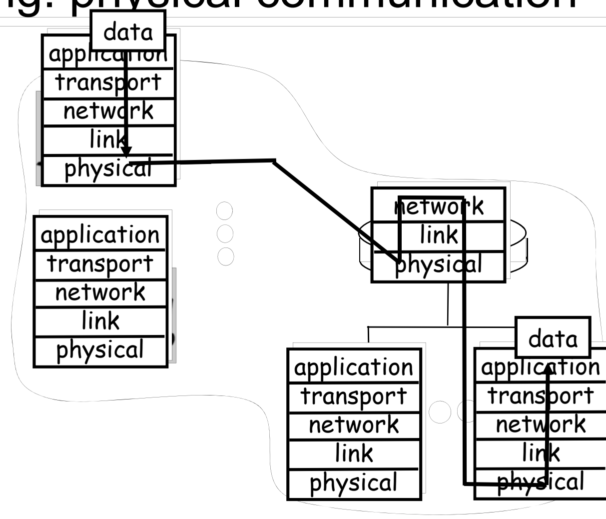
For example: transport

- take data from app
- add addressing, reliability check info to form packet
- send datagram to peer
- wait for peer to ack receipt
- analogy: post office



From: *Computer Networking: A Top Down Approach Featuring the Internet*, 2nd edition. Jim Kurose, Keith Ross Addison-Wesley, July 2002.

Layering: physical communication



From: *Computer Networking: A Top Down Approach Featuring the Internet*, 2nd edition. Jim Kurose, Keith Ross Addison-Wesley, July 2002.

Common Protocol Functions

- Encapsulation
- Fragmentation and reassembly
- Connection control
- Ordered delivery
- Flow control
- Error control
- Addressing
- Multiplexing
- Transmission services

Common Protocol Functions

- Encapsulation→ adding control information, e.g.,
  - Address
  - Error detection/correction bits
  - Protocol control
- Fragmentation and reassembly
  - Max packet size

Common Protocol Functions

- Connection control – Not all protocols use connections
  - Connection oriented
  - Signaling
  - Graceful set-up and tear-down
- Ordered delivery
  - Deal with reordering
  - Lost packets

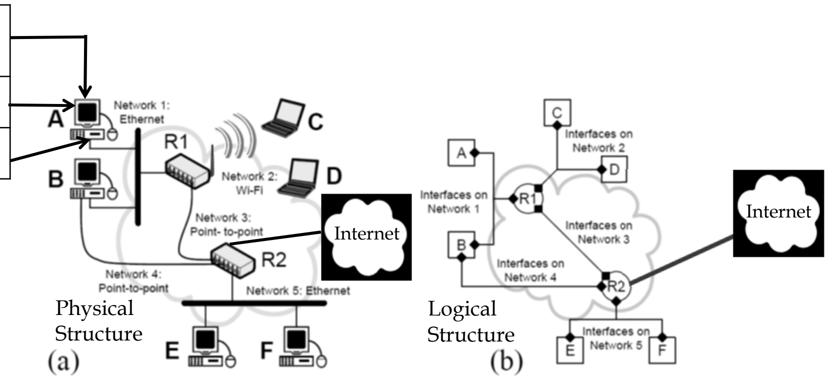
Common Protocol Functions

- Flow control
  - Match transmit and receiving rates
  - Prevent over running buffers
- Error control
  - Error detection
  - Error correction
  - Adds bits to packets
  - Detected errors sometimes causes retransmissions

Common Protocol Functions

- Addressing
  - Different layers contain different addressed, e.g., Link Layer (Medium Access Control (MAC)) address, Network Address (IP address), and Transport address (socket)

Application Interface (TCP/UDP)	Socket Address
Internetwork Interface	IP address
Physical Interface (Layer 2 address)	MAC address

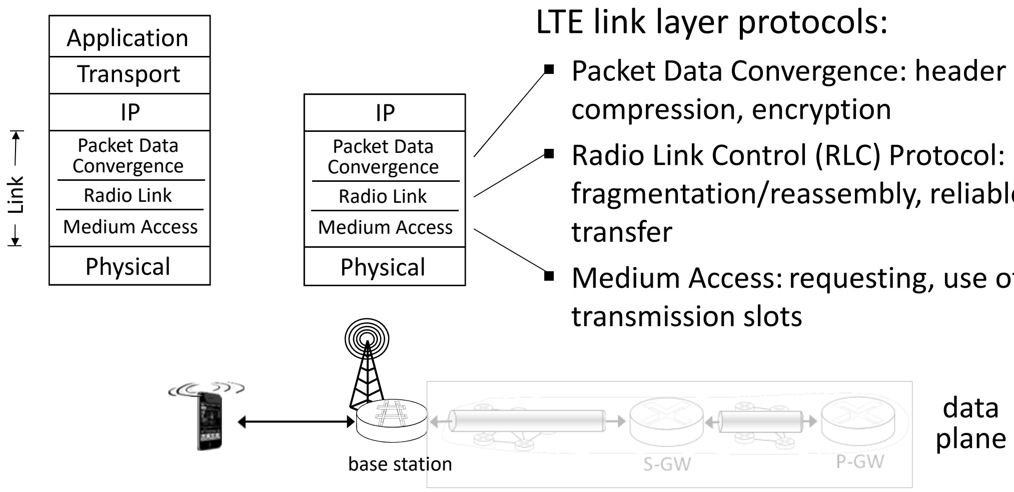


Modified from: Computer Networks: Performance and Quality of Service, Ivan Marsic, Rutgers University, http://www.ece.rutgers.edu/~marsic/books/CN/

Common Protocol Functions

- Multiplexing
  - Enables multiple customers to use one “pipe”
    - MAC address allows sharing on LAN
    - In TDM address is the time slot
    - In the internet host id is the IP address
    - Socket addresses allow multiple applications to use the same IP address
- Transmission services,
  - Quality of Service (QoS) – Guarantees of Service, maybe statistical, e.g., average delay < Threshold
  - Class of Service (CoS) – No guarantees of Service, priority service
  - Security
  - Other “layer” specific services, e.g., framing

LTE data plane protocol stack: first hop

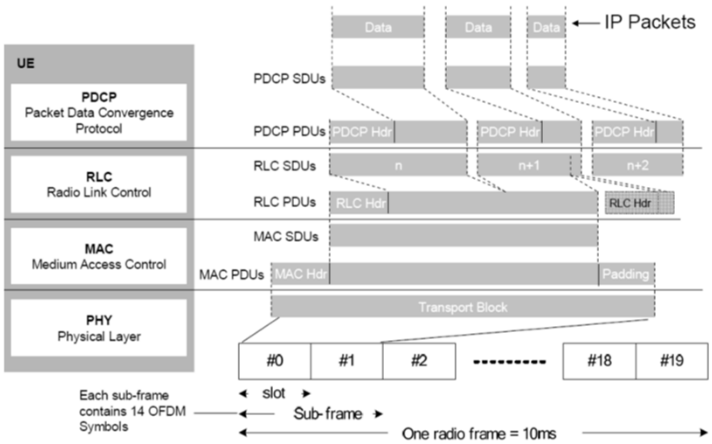


LTE link layer protocols:

- Packet Data Convergence: header compression, encryption
- Radio Link Control (RLC) Protocol: fragmentation/reassembly, reliable data transfer
- Medium Access: requesting, use of radio transmission slots

Modified from: 8th edition Jim Kurose, Keith Ross Pearson, 2020

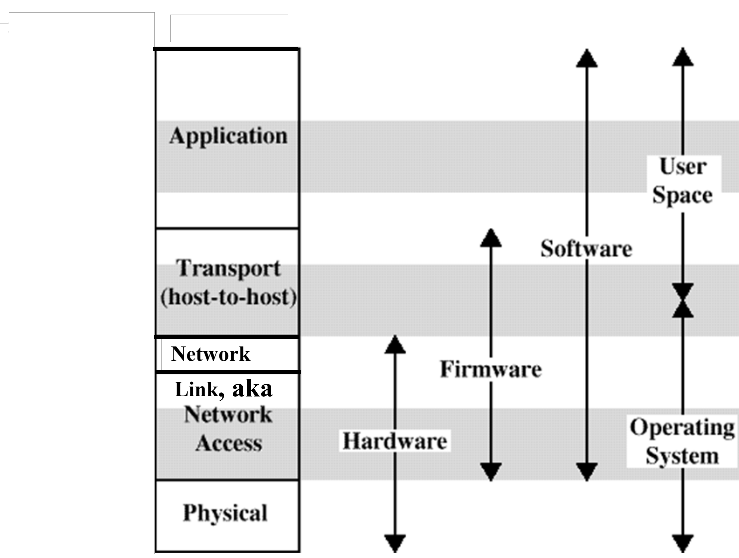
Example: LTE Protocol Stack



- Protocol Data Units (PDU) = packets between Peer entities
- Service Data Units (SDU)= packets between layers

From: https://www.nxp.com/files-static/wireless_comm/doc/white_paper/LTEPTCLOVWWP.pdf

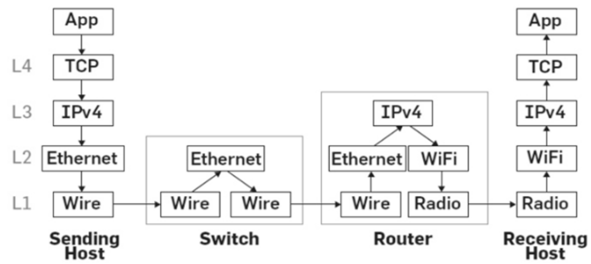
Implementation of Layered Architecture



From: High -Speed Networks, W. Stallings,Prentice Hall, 1998

Internet design choices

- Service model-Best effort
- Layered architecture
- Mechanisms
  - Routing
  - End-to-end reliability
  - Naming/addressing



Reference: Extracting the Essential Simplicity of the Internet, By James Mccauley, Scott Shenker, George Varghese, Communications of the ACM, February 2023, Vol. 66 No. 2, Pages 64-74

Summary

- Internet Architecture
- Standards
  - Who makes them?
  - Why? (Advantages/disadvantages)
- Layered Architecture
  - Network architecture (layered) model
  - Encapsulation
- Common Protocol Functions