16: Application, Transport, Network and Link Layers

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Roadmap

- Application Layer (User level)
- Transport Layer (OS)
- Network Layer (OS)
- Link Layer (Device Driver, Adapter Card)

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Application Layer

- Network Applications Drive Network Design
- Important to remember that network applications are the reason we care about building a network infrastructure
- Applications range from text based command line ones popular in the 1980s (like telnet, ftp, news, chat, etc) to multimedia applications (Web browsers, audio and video streaming, realtime videoconferencing, etc.)

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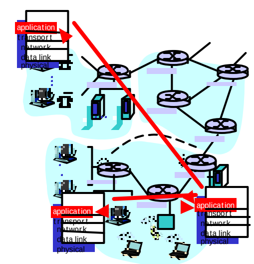
Applications and application-layer protocols

Application: communicating, distributed processes

- running in network hosts in "user space"
- exchange messages to implement app
- e.g., email, file transfer, the Web

Application-layer protocols

- one "piece" of an app
- define messages exchanged by apps and actions taken
- user services provided by lower layer protocols



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Client-server paradigm

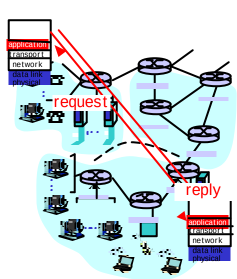
Typical network app has two pieces: *client* and *server*

Client:

- initiates contact with server ("speaks first")
- typically requests service from server,
- for Web, client is implemented in browser; for e-mail, in mail reader

Server:

- Running first (always?)
- provides requested service to client e.g., Web server sends requested Web page, mail server delivers e-mail



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How do clients and servers communicate?

API: application programming interface

- defines interface between application and transport layer
- socket: Internet API
  - two processes communicate by sending data into socket, reading data out of socket

Q: how does a process "identify" the other process with which it wants to communicate?

- IP address of host running other process
- "port number" - allows receiving host to determine which local process the message should be delivered

… more on this later.

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Socket programming

Goal: learn how to build client/server application that communicate using sockets

Socket API
- introduced in BSD4.1 UNIX, 1981
- Sockets are explicitly created, used, released by applications
- client/server paradigm
- two types of transport service via socket API:
  - unreliable datagram
  - reliable, byte stream-oriented

socket

a *host-local*, *application-created/owned*, *OS-controlled* interface (a "door") into which application process can both send and receive messages to/from another (remote or local) application process

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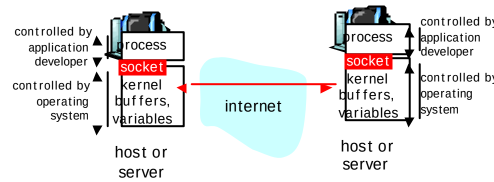
Sockets

Socket: a door between application process and end-end-transport protocol (UCP or TCP)



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Languages and Platforms

- Socket API is available for many languages on many platforms:
  - C, Java, Perl, Python,...
  - *nix, Windows,...
- Socket Programs written in any language and running on any platform can communicate with each other!
- Client and server must agree on the type of socket, the server port number and the protocol

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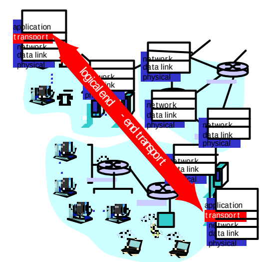
Transport services and protocols

- provide *logical communication* between app' processes running on different hosts
- transport protocols run in end systems
- transport vs network layer services:
- *network layer:* data transfer between **end systems**
- *transport layer:* data transfer between **processes**
  - relies on, enhances, network layer services



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Services provided by Internet transport protocols

TCP service:
- *connection-oriented:* setup required between client, server
- *reliable transport* between sending and receiving process
- *flow control:* sender won't overwhelm receiver
- *congestion control:* throttle sender when network overloaded
- *does not providing:* timing, minimum bandwidth guarantees

UDP service:
- unreliable data transfer between sending and receiving process
- does not provide: connection setup, reliability, flow control, congestion control, timing, or bandwidth guarantee

Q: why bother? Why is there a UDP?

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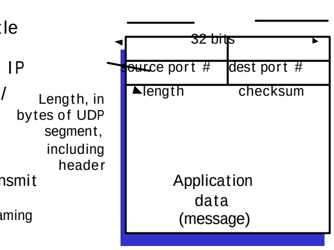
UDP

- UDP adds very little functionality (or overhead) to bare IP
- Adds multiplexing/demultiplexing
- other UDP uses (why?):
  - DNS: small, retransmit if necessary
  - often used for streaming multimedia apps
    - Loss tolerant
    - rate sensitive



UDP segment format

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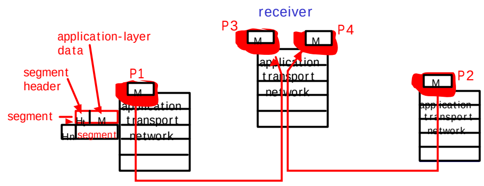
Process-to-Process Message Delivery

Goal : Deliver application data to correct process (and more particularly to the right socket)

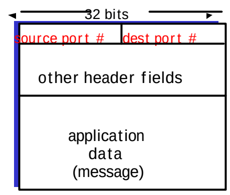
Segment - unit of data exchanged between transport layer entities; transport protocol data unit (TPDU)



Multiplexing/demultiplexing

Multiplexing:
gathering data from multiple app processes, enveloping data with header (later used for demultiplexing)

Demultiplexing:
Stream of incoming data into one machine separated into smaller streams destined for individual processes



TCP/UDP segment format

Demultiplexing based on IP addresses of sender and and port numbers of both sender and receiver

- Can distinguish traffic coming to same port but part of separate conversations (like multiple client connections to a web server)

TCP adds functionality

- TCP adds lots of functionality over bare IP and over UDP
  - Still has multiplexing/demultiplexing
  - Adds reliable, in-order delivery
  - Adds flow control and congestion control
- How can you guarantee that other side gets "A B C D E" when network could:
  - Lose data "A B D E"
  - Duplicate data "A B C C D E"
  - Corrupt data "A B X D E"
  - Reorder data "A C D E B"
  - Or all of the above!

Common Sense

- Consider faxing a document with flaky machine
  - Can't talk to person on the other side any other way
- What would you do to make sure they got the transmission?
  - Number the pages – so receiver can put them in order/detect duplicates/detect losses
  - Need feedback from the receiver!!!
  - Resend data that is missing or if don't hear from receiver
- Put some info on cover sheet that lets person verify fax info (summarize info like checksum)
- What if it is a really big document? Receiver might like to be able to tell you send first 10 pages then 10 more…

TCP Connection Management

Recall: TCP sender, receiver establish "connection" before exchanging data segments

- initialize TCP variables:
  - seq. #s
  - buffers, flow control info (e.g. **RcvWindow**)
- *client:* connection initiator

```
Socket clientSocket = new
Socket("hostname","port
number");
```

- *server:* contacted by client

```
Socket connectionSocket =
welcomeSocket.accept();
```

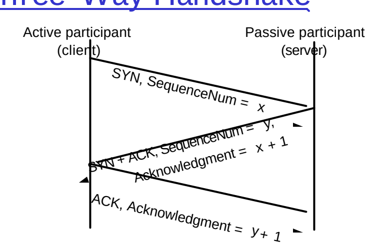
Three way handshake:

Step 1: client end system sends TCP SYN control segment to server
- specifies initial seq #

Step 2: server end system receives SYN, replies with SYNACK control segment
- ACKs received SYN
- allocates buffers
- specifies server-> receiver initial seq. #

Step 3: client acknowledges servers initial seq. #

Three-Way Handshake



Note: SYNs take up a sequence number even though no data bytes

Timeout and Retransmission

- Receiver must acknowledge receipt of all packets
- Sender sets a timer if acknowledgement has not arrived before timer expires then sender will retransmit packet
- Adaptive retransmission: timer value computed as a function of average round trip times and variance

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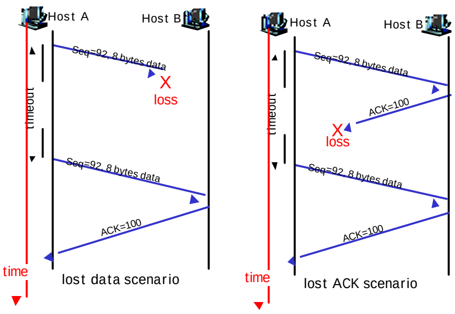
TCP: retransmission scenarios (1)



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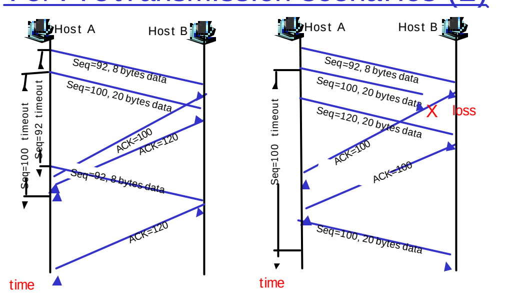
TCP: retransmission scenarios (2)



premature timeout, cumulative ACKs

Duplicate ACK, fast retransmit (really need 3 dup acks before fast retransmit)

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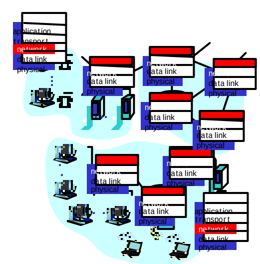
Network layer functions

- transport packet from sending to receiving hosts
- network layer protocols in *every* host, router (Recall transport layer is end-to-end)

three important functions:

- *path determination:* route taken by packets from source to dest. *Routing algorithms*
- *switching:* move packets from router's input to appropriate router output
- *call setup:* some network architectures (e.g. telephone, ATM) require router call setup along path before data flow



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Internet Protocol

- The Internet is a network of **heterogeneous** networks:
  - using different technologies (ex. different maximum packet sizes)
  - belonging to different administrative authorities (ex. Willing to accept packets from different addresses)
- Goal of IP: interconnect all these networks so can send end to end without any knowledge of the intermediate networks
- Routers, switches, bridges: machines to forward packets between heterogeneous networks

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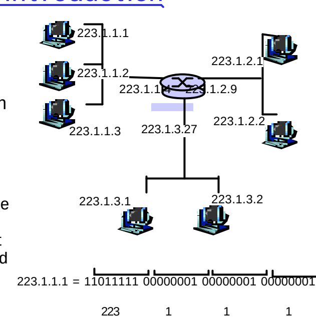
IP Addressing: introduction

- IP address: 32-bit identifier for host, router *interface*
- *interface:* connection between host and physical link
  - router's must have multiple interfaces
  - host may have multiple interfaces
  - IP addresses (unicast addresses) associated with interface, not host, router



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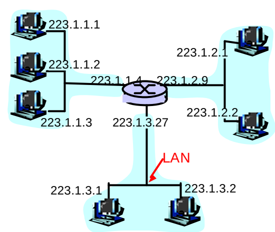
IP Addressing

- IP address:
  - 32 bits
  - network part (high order bits)
  - host part (low order bits)
  - Defined by class of IP address?
  - Defined by subnet mask
- *What's a network ?* (from IP address perspective)
  - device interfaces with same network part of IP address
  - can physically reach each other without intervening router

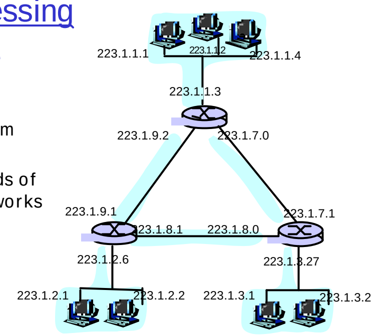


network consisting of 3 IP networks (223.1.1, 223.1.2, 223.1.3)

IP Addressing

How to find the networks?

- Detach each interface from router, host
- create "islands of isolated networks

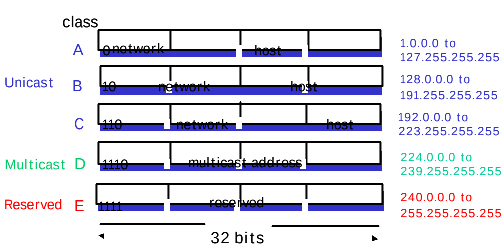


Interconnected system consisting of six networks

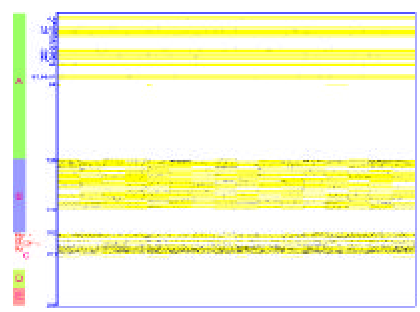
IP Addresses (Classes)

given notion of "network", let's re-examine IP addresses:

"class- full" addressing



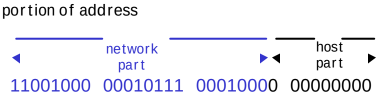
IP Address Space Allocation



CAIDA 1998

IP addressing: CIDR

- classful addressing:
  - inefficient use of address space, address space exhaustion
  - e.g., class B net allocated enough addresses for 65K hosts, even if only 2K hosts in that network
- CIDR: Classless InterDomain Routing
  - network portion of address of arbitrary length
  - address format: a.b.c.d/x, where x is # bits in network portion of address



200.23.16.0/23

Recall: How to get an IP Address?

- Answer 1: Normally, answer is get an IP address from your upstream provider
  - This is essential to maintain efficient routing!
- Answer 2: If you need lots of IP addresses then you can acquire your own block of them.
  - IP address space is a scarce resource - must prove you have fully utilized a small block before can ask for a larger one and pay $$ (Jan 2002 - $2250/year for /20 and $18000/year for a /14)

How to get lots of IP Addresses? Internet Registries

RIPE NCC (Riseaux IP Europiens Network Coordination Centre) for Europe, Middle-East, Africa

APNIC (Asia Pacific Network Information Centre) for Asia and Pacific

ARIN (American Registry for Internet Numbers) for the Americas, the Caribbean, sub-saharan Africa

Note: Once again regional distribution is important for efficient routing!

Can also get Autonomous System Numbers (ASNs) from these registries

Classful vs Classless

- Class A = /8
- Class B = /16
- Class C = /24

IP addresses: how to get one? revisted

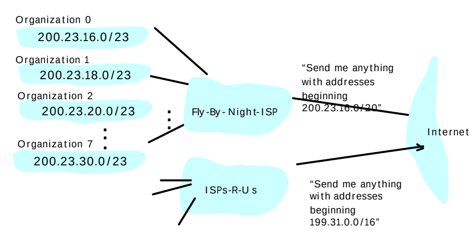
Network (network portion):

- get allocated portion of ISP's address space:

ISP's block	11001000 00010111 00010000 00000000	200.23.16.0/20
Organization 0	11001000 00010111 00010000 00000000	200.23.16.0/23
Organization 1	11001000 00010111 00010010 00000000	200.23.18.0/23
Organization 2	11001000 00010111 00010100 00000000	200.23.20.0/23
...	....	....
Organization 7	11001000 00010111 00011110 00000000	200.23.30.0/23

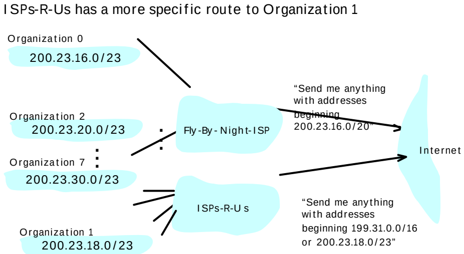
Hierarchical addressing: route aggregation

Hierarchical addressing allows efficient advertisement of routing information:



Hierarchical addressing: more specific routes

ISPs-R-Us has a more specific route to Organization 1



IP Address Allocation

- CIDR is great but must work around existing allocations of IP address space
  - Company 1 has a /20 allocation and has given out sub portions of it to other companies
  - University has a full class B address
  - Company 2 has a /23 allocation from some other class B
  - ALL use the same upstream ISP – that ISP must advertise routes to all these blocks that cannot be described with a simple CIDR network ID and mask!
- Estimated reduction in routing table size with CIDR
  - If IP addresses reallocated, CIDR applied to all, IP addresses reallocated based on geographic and service provider divisions that current routing tables with 10000+ entries could be reduced to 200 entries [Ford, Rekhter and Brown 1993]
  - How stable would that be though? Leases for all?

Current Allocation

- Interesting to exam current IP address space allocation (who has class A's ? Etc)
  - Who has A's?
  - Computer companies around during initial allocation (IBM, Apple)
  - Universities (Stanford, MIT)
  - CAIDA has info on complete allocation

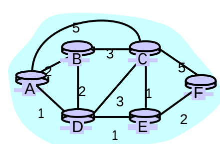
Routing

- IP Routing – each router is supposed to send each IP datagram one step closer to its destination
- How do they do that?
  - Hierarchical Routing – in ideal world would that be enough? Well its not an ideal world
  - Other choices
    - Static Routing
    - Dynamic Routing
      - Before we cover specific routing protocols we will cover principles of dynamic routing protocols

Routing

Routing protocol

Goal: determine "good" path (sequence of routers) thru network from source to dest.



Graph abstraction for routing algorithms:

- graph nodes are routers
- graph edges are physical links
  - link cost: delay, $ cost, or congestion level

- "good" path:
  - typically means minimum cost path
  - other definitions possible

Routing Algorithm classification: Static or Dynamic?

Choice 1: Static or dynamic?

Static:
- routes change slowly over time
- Configured by system administrator
- Appropriate in some circumstances, but obvious drawbacks (routes added/removed? sharing load?)
- Not much more to say?

Dynamic:
- routes change more quickly
  - periodic update
  - in response to link cost changes

Routing Algorithm classification: Global or decentralized?

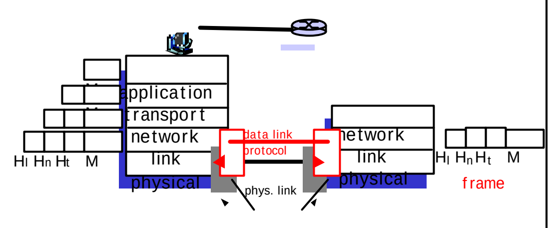
Choice 2, if dynamic: global or decentralized information?

Global:
- all routers have complete topology, link cost info
- "link state" algorithms

Decentralized:
- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors (gossip)
- "distance vector" algorithms

Link Layer: setting the context

- two *physically connected* devices:
  - host-router, router-router, host-host
- unit of data: *frame*



Link Layer Services

- Framing, link access:
  - encapsulate datagram into frame, adding header, trailer
  - implement channel access if shared medium,
  - 'physical addresses' used in frame headers to identify source, dest
    - different from IP address!
- Reliable delivery between two physically connected devices:
  - Reliable delivery over an unreliable link (like TCP but done at link layer)
  - seldom used on low bit error link (fiber, some twisted pair)
  - wireless links: high error rates
    - Q: why both link-level and end-end reliability?

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Link Layer Services (more)

- Flow Control:
  - pacing between sender and receivers
- *Error Detection*:
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors:
    - signals sender for retransmission or drops frame
- Error Correction:
  - receiver identifies *and corrects* bit error(s) without resorting to retransmission

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Multiple Access Links and Protocols

Three types of "links":

- broadcast (shared wire or medium; e.g, Ethernet, Wavelan, etc.)

- point-to-point (single wire, e.g. PPP, SLIP)
- switched (e.g., switched Ethernet, ATM etc)

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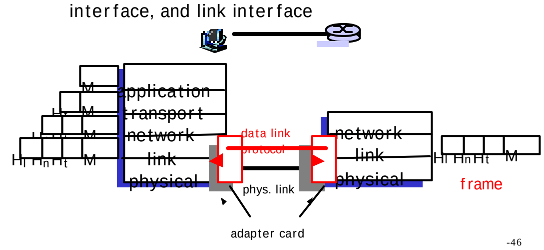
Link Layer: Implementation

- implemented in "adapter"
  - e.g., PCMCIA card, Ethernet card
  - typically includes: RAM, DSP chips, host bus interface, and link interface



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Multiple Access protocols

- single shared communication channel
- two or more simultaneous transmissions by nodes: interference
  - only one node can send successfully at a time
- *multiple access protocol:*
  - distributed algorithm that determines how stations share channel, i.e., determine when station can transmit
- claim: humans use multiple access protocols all the time

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CSMA: Carrier Sense Multiple Access

CSMA: listen before transmit:

- If channel sensed idle: transmit entire pkt
- If channel sensed busy, defer transmission
  - Persistent CSMA: retry immediately with probability p when channel becomes idle (may cause instability)
  - Non-persistent CSMA: retry after random interval
- human analogy: don't interrupt others!

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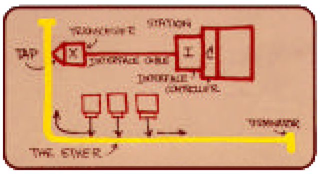
Ethernet

"dominant" LAN technology:

- cheap $20 for 100Mbs!
- first widely used LAN technology
- Simpler, cheaper than token LANs and ATM
- Kept up with speed race: 10, 100, 1000 Mbps
- Uses CSMA with collision detection



Metcalfe's Ethernet sketch

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