15-441: Computer Networking

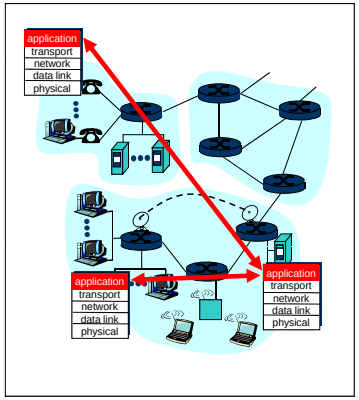
Lecture 4: Design Philosophy & Applications

Lecture Overview

- Last time:
  - Protocol stacks and layering
  - OSI and TCP/IP models
- Application requirements
- Application examples
  - http
- Project information
- Internet Architecture

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



Client-Server Paradigm

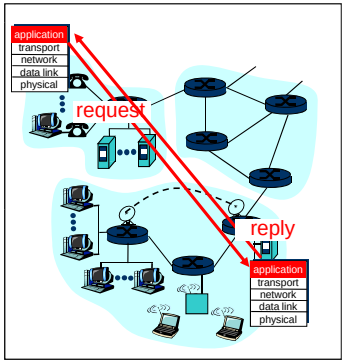
Typical network app has two pieces: *client* and *server*

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

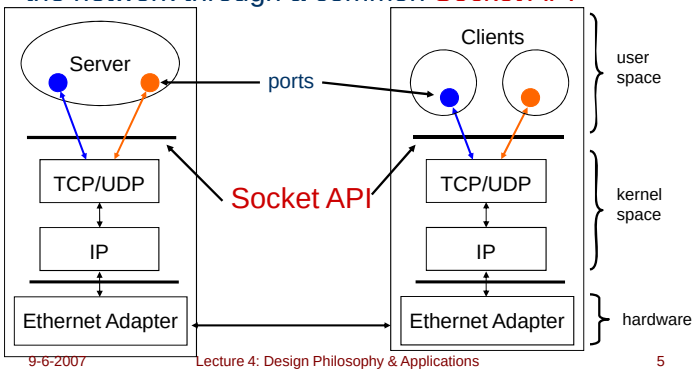
Server:

- Provides requested service to client
- e.g., Web server sends requested Web page, mail server delivers e-mail

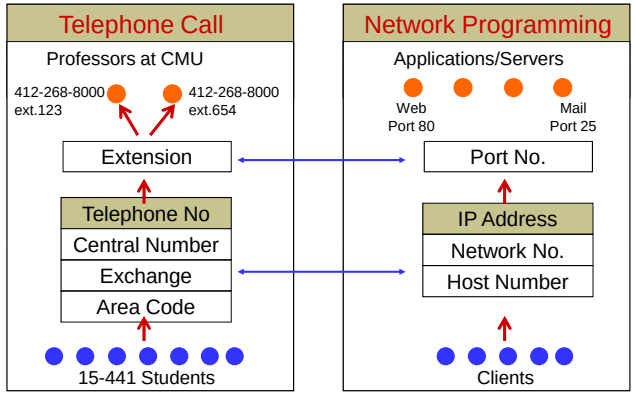


Server and Client

Server and Client exchange messages over the network through a common Socket API



Network Addressing Analogy



What Service Does an Application Need?

Data loss

- Some apps (e.g., audio) can tolerate some loss
- Other apps (e.g., file transfer, telnet) require 100% reliable data transfer

Timing

- Some apps (e.g., Internet telephony, interactive games) require low delay to be "effective"

Bandwidth

- Some apps (e.g., multimedia) require minimum amount of bandwidth to be "effective"
- Other apps ("elastic apps") make use of whatever bandwidth they get

Transport Service Requirements of Common Apps

Application	Data loss	Bandwidth	Time Sensitive
file transfer	no loss	elastic	no
e-mail	no loss	elastic	no
web documents	no loss	elastic	no
real-time audio/ video	loss-tolerant	audio: 5Kb-1Mb video:10Kb-5Mb	yes, 100's msec
stored audio/video	loss-tolerant	same as above	yes, few secs
interactive games	loss-tolerant	few Kbps	yes, 100's msec
financial apps	no loss	elastic	yes and no

Other Requirements

- Network reliability
  - Network service must always be available
- Security: privacy, denial of service, authentication, …
- Scalability.
  - Scale to large numbers of users, traffic flows, …
- Manageability: monitoring, control, …

User Datagram Protocol(UDP): An Analogy

UDP	Postal Mail
• Single socket to receive messages • No guarantee of delivery • Not necessarily in-order delivery • Datagram – independent packets • Must address each packet	• Single mailbox to receive letters • Unreliable ☺ • Not necessarily in-order delivery • Letters sent independently • Must address each reply

Example UDP applications
Multimedia, voice over IP

Transmission Control Protocol (TCP): An Analogy

TCP	Telephone Call
• Reliable – guarantee delivery • Byte stream – in-order delivery • Connection-oriented – single socket per connection • Setup connection followed by data transfer	• Guaranteed delivery • In-order delivery • Connection-oriented • Setup connection followed by conversation

Example TCP applications
Web, Email, Telnet

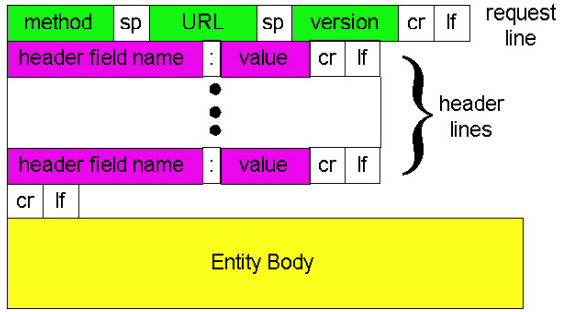
HTTP Basics

- HTTP layered over bidirectional byte stream
  - Almost always TCP
- Interaction
  - Client sends request to server, followed by response from server to client
  - Requests/responses are encoded in text
- Stateless
  - Server maintains no information about past client requests

How to Mark End of Message?

- Size of message → Content-Length
  - Must know size of transfer in advance
- Delimiter → MIME style Content-Type
  - Server must “escape” delimiter in content
- Close connection
  - Only server can do this

HTTP Request



HTTP Request

- Request line
  - Method
    - GET – return URI
    - HEAD – return headers only of GET response
    - POST – send data to the server (forms, etc.)
  - URI
    - E.g. http://www.intel-iris.net/index.html with a proxy
    - E.g. /index.html if no proxy
  - HTTP version

HTTP Request

- Request headers
  - Authorization – authentication info
  - Acceptable document types/encodings
  - From – user email
  - If-Modified-Since
  - Referrer – what caused this page to be requested
  - User-Agent – client software
- Blank-line
- Body

HTTP Request Example

GET / HTTP/1.1
Accept: */*
Accept-Language: en-us
Accept-Encoding: gzip, deflate
User-Agent: Mozilla/4.0 (compatible; MSIE 5.5; Windows NT 5.0)
Host: www.intel-iris.net
Connection: Keep-Alive

HTTP Response

- Status-line
  - HTTP version
  - 3 digit response code
    - 1XX – informational
    - 2XX – success
      - 200 OK
    - 3XX – redirection
      - 301 Moved Permanently
      - 303 Moved Temporarily
      - 304 Not Modified
    - 4XX – client error
      - 404 Not Found
    - 5XX – server error
      - 505 HTTP Version Not Supported
  - Reason phrase

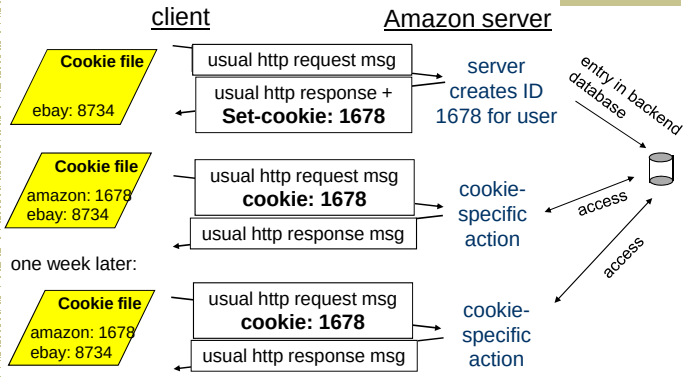
HTTP Response

- Headers
  - Location – for redirection
  - Server – server software
  - WWW-Authenticate – request for authentication
  - Allow – list of methods supported (get, head, etc)
  - Content-Encoding – E.g x-gzip
  - Content-Length
  - Content-Type
  - Expires
  - Last-Modified
- Blank-line
- Body

HTTP Response Example

HTTP/1.1 200 OK
Date: Tue, 27 Mar 2001 03:49:38 GMT
Server: Apache/1.3.14 (Unix) (Red-Hat/Linux) mod_ssl/2.7.1 OpenSSL/0.9.5a DAV/1.0.2 PHP/4.0.1pl2 mod_perl/1.24
Last-Modified: Mon, 29 Jan 2001 17:54:18 GMT
ETag: "7a11f-10ed-3a75ae4a"
Accept-Ranges: bytes
Content-Length: 4333
Keep-Alive: timeout=15, max=100
Connection: Keep-Alive
Content-Type: text/html
.....

Cookies: Keeping "State"

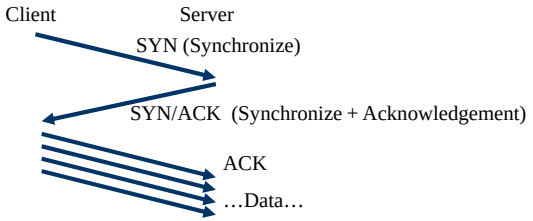


Typical Workload (Web Pages)

- Multiple (typically small) objects per page
- File sizes
  - Why different than request sizes?
  - Also heavy-tailed
    - Pareto distribution for tail
    - Lognormal for body of distribution
- Embedded references
  - Number of embedded objects = pareto – $p(x) = ak^a x^{-(a+1)}$

Aside: TCP

- TCP connections need to be set up
  - "Three Way Handshake":

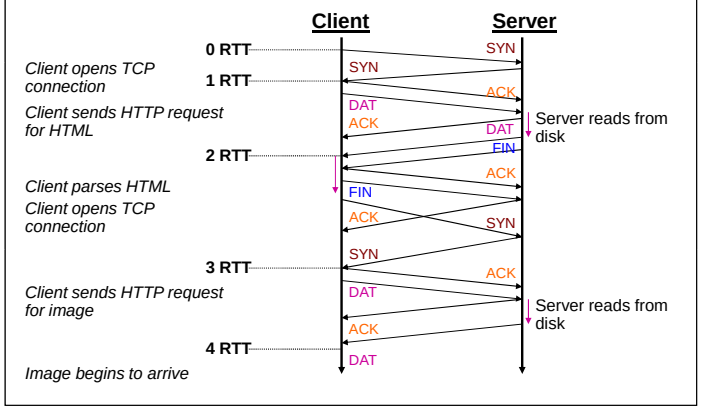


- TCP transfers start slowly and then ramp up the bandwidth used (so they don't use too much)

HTTP 0.9/1.0

- One request/response per TCP connection
  - Simple to implement
- Disadvantages
  - Multiple connection setups → three-way handshake each time
    - Several extra round trips added to transfer
  - Multiple slow starts

Single Transfer Example



Netscape Solution

- Mosaic (original popular Web browser) fetched one object at a time!
- Netscape uses multiple concurrent connections to improve response time
  - Different parts of Web page arrive independently
  - Can grab more of the network bandwidth than other users
- Doesn't necessarily improve response time
  - TCP loss recovery ends up being timeout dominated because windows are small

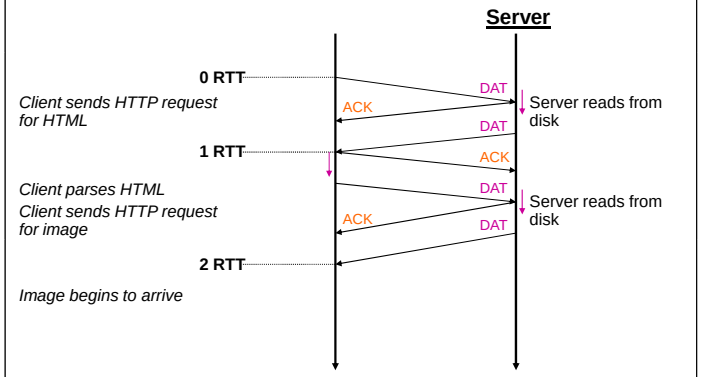
Performance Issues

- Short transfers are hard on TCP
  - Stuck in slow start
  - Loss recovery is poor when windows are small
- Lots of extra connections
  - Increases server state/processing
- Servers also hang on to connection state after the connection is closed
  - Why must server keep these?
  - Tends to be an order of magnitude greater than # of active connections, why?

Persistent Connection Solution

- Multiplex multiple transfers onto one TCP connection
- How to identify requests/responses
  - Delimiter → Server must examine response for delimiter string
  - Content-length and delimiter → Must know size of transfer in advance
  - Block-based transmission → send in multiple length delimited blocks
  - Store-and-forward → wait for entire response and then use content-length
  - Solution → use existing methods and close connection otherwise

Persistent Connection Solution



Project 1 (& 2)

- Out yesterday, due 9/25
  - Two checkpoints (9/11 and 9/18)
  - Get started early. Get started early. Get …
- Project partners
  - Choose very soon
  - Mail to Albert Sheu (albert@cmu.edu)
- Project 1 is an IRC server (Internet Relay Chat)
  - Text-based chat protocol
  - Basic server (connect, channels, talk, etc.)
- Project 2
  - Add multicast and unicast routing to a collection of IRC servers
  - Will be released next week

Project 1 goals

- Skill with real network applications
  - Select, dealing with multiple streams of data, remote clients and servers
  - Protocol “grunge” - headers, layers, packets, etc.
  - Be able to implement a [whatever] server.
- Meet a real protocol
  - Create it from the spec
- Don’t be dismayed by the size of the handout. It breaks down into reasonable chunks.

Internet Architecture

- Background
  - “The Design Philosophy of the DARPA Internet Protocols” (David Clark, 1988).
- Fundamental goal: effective network interconnection
- Goals, *in order of priority:*
  1. Continue despite loss of networks or gateways
  2. Support multiple types of communication service
  3. Accommodate a variety of networks
  4. Permit distributed management of Internet resources
  5. Cost effective
  6. Host attachment should be easy
  7. Resource accountability

Priorities

- The effects of the order of items in that list are still felt today
  - E.g., resource accounting is a hard, current research topic
- Let's look at them in detail

Survivability

- If network disrupted and reconfigured
  - Communicating entities should not care!
  - No higher-level state reconfiguration
  - Ergo, transport interface only knows "working" and "not working." Not working == complete partition.
- How to achieve such reliability?
  - Where can communication state be stored?

	Network	Host
Failure handing	**Replication**	**"Fate sharing"**
Net Engineering	**Tough**	**Simple**
Switches	**Maintain state**	**Stateless**
Host trust	**Less**	**More**

Fate Sharing

- Lose state information for an entity if (and only if?) the entity itself is lost.
- Examples:
  - OK to lose TCP state if one endpoint crashes
    - NOT okay to lose if an intermediate router reboots
  - Is this still true in today's network?
    - NATs and firewalls
- Survivability compromise: Heterogeneous network → less information available to end hosts and Internet level recovery mechanisms

Types of Service

- Recall TCP vs. UDP
  - Elastic apps that need reliability: remote login or email
  - Inelastic, loss-tolerant apps: real-time voice or video
  - Others in between, or with stronger requirements
  - Biggest cause of delay variation: reliable delivery
    - Today's net: ~100ms RTT
    - Reliable delivery can add *seconds*.
- Original Internet model: "TCP/IP" one layer
  - First app was remote login…
  - But then came debugging, voice, etc.
  - These differences caused the layer split, added UDP
- No QoS support assumed from below
  - In fact, some underlying nets only supported reliable delivery
    - Made Internet datagram service less useful!
  - Hard to implement without network support
  - QoS is an ongoing debate…

Varieties of Networks

- Several “networks” already existed
  - Interconnect the ARPANET, X.25 networks, LANs, satellite networks, packet networks, serial links…
- Minimum set of assumptions for underlying net
  - Minimum packet size
  - Reasonable delivery odds, but not 100%
  - Some form of addressing unless point to point
- Important non-assumptions:
  - Perfect reliability
  - Broadcast, multicast
  - Priority handling of traffic
  - Internal knowledge of delays, speeds, failures, etc.
- Much engineering then only has to be done once

The “Other” goals

- Management
  - Today’s Internet is decentralized - BGP
  - Very coarse tools. Still in the “assembly language” stage
- Cost effectiveness
  - Economies of scale won out
  - Internet cheaper than most dedicated networks
  - Packet overhead less important by the year
- Attaching a host
  - Not awful; DHCP and related autoconfiguration technologies helping. A ways to go, but the path is there
- But…

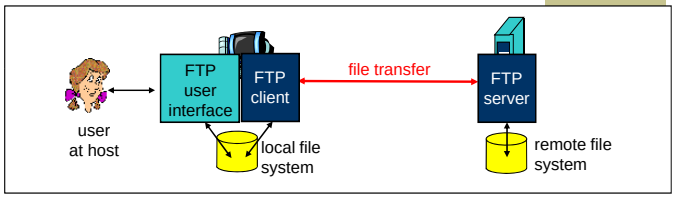
Accountability

- Huge problem.
- Accounting
  - Billing? (mostly flat-rate. But phones are moving that way too - people like it!)
  - Inter-provider payments
    - Hornet’s nest. Complicated. Political. Hard.
- Accountability and security
  - Huge problem.
  - Worms, viruses, etc.
    - Partly a host problem. But hosts very trusted.
  - Authentication
    - Purely optional. Many philosophical issues of privacy vs. security

Readings

- “End-to-end arguments in system design”, Saltzer, Reed, and Clark, ACM Transactions on Computer Systems, November 1984.
- “The design philosophy of the DARPA Internet Protocols”, Dave Clark, SIGCOMM 88.

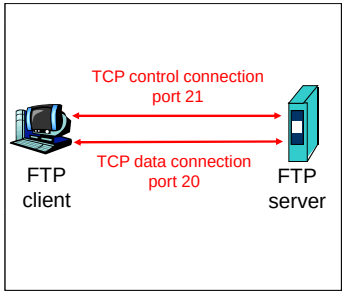
FTP: The File Transfer Protocol



- Transfer file to/from remote host
- Client/server model
  - *Client:* side that initiates transfer (either to/from remote)
  - *Server:* remote host
- ftp: RFC 959
- ftp server: port 21

Ftp: Separate Control, Data Connections

- Ftp client contacts ftp server at port 21, specifying TCP as transport protocol
- Two parallel TCP connections opened:
  - Control: exchange commands, responses between client, server.
    "out of band control"
  - Data: file data to/from server
- Ftp server maintains "state": current directory, earlier authentication



Ftp Commands, Responses

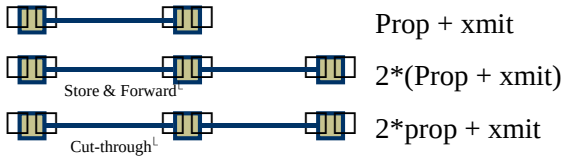
Sample Commands:

- sent as ASCII text over control channel
- `USER` *`username`*
- `PASS` *`password`*
- `LIST` return list of files in current directory
- `RETR filename` retrieves (gets) file
- `STOR filename` stores (puts) file onto remote host

Sample Return Codes

- status code and phrase
- `331 Username OK, password required`
- `125 data connection already open; transfer starting`
- `425 Can't open data connection`
- `452 Error writing file`

Packet Delay



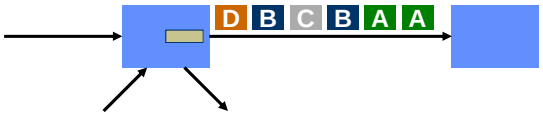
When does cut-through matter?

Next: Routers have finite speed (processing delay)

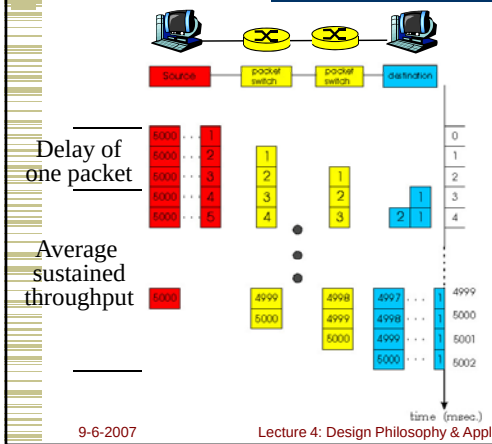
Routers may buffer packets (queuing delay)

Packet Delay

- Sum of a number of different delay components.
- Propagation delay on each link.
  - Proportional to the length of the link
- Transmission delay on each link.
  - Proportional to the packet size and 1/link speed
- Processing delay on each router.
  - Depends on the speed of the router
- Queuing delay on each router.
  - Depends on the traffic load and queue size



Application-level Delay



Delay of one packet

Average sustained throughput

$$\text{Delay}^{*} + \frac{\text{Size}}{\text{Throughput}}$$

Units: seconds + bits/(bits/seconds)

* For minimum sized packet

Some Examples

- How long does it take to send a 100 Kbit file?
  - Assume a perfect world
  - And a 10 Kbit file

Latency \ Throughput	100 Kbit/s	1 Mbit/s	100 Mbit/s
500 µsec			
10 msec			
100 msec			

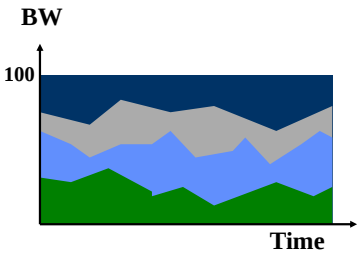
Back to performance

- We examined delay,
- But what about throughput?

- Important factors:
  - Link capacity
  - *Other traffic*

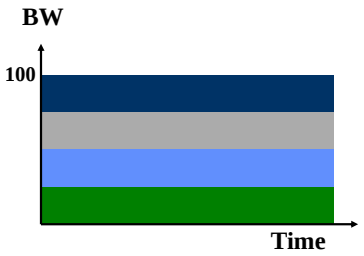
Bandwidth Sharing

- Bandwidth received on the bottleneck link determines end-to-end throughput.
- Router before the bottleneck link decides how much bandwidth each user gets.
  - Users that try to send at a higher rate will see packet loss
- User bandwidth can fluctuate quickly as flows are added or end, or as flows change their transmit rate.

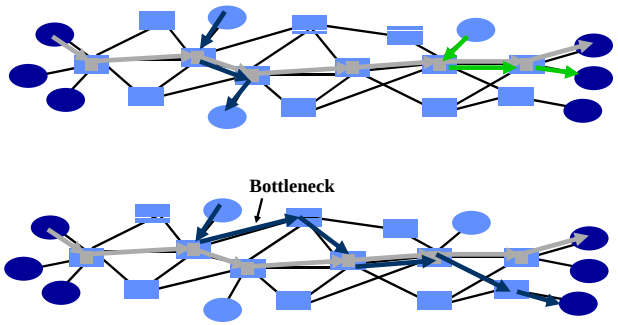


Fair Sharing of Bandwidth

- All else being equal, fair means that users get equal treatment.
  - Sounds fair
- When things are not equal, we need a policy that determines who gets how much bandwidth.
  - Users who pay more get more bandwidth
  - Users with a higher "rank" get more bandwidth
  - Certain classes of applications get priority

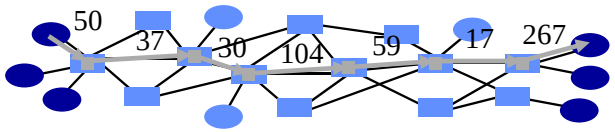


But It is Not that Simple



Sustained Throughput

- When streaming packets, the network works like a pipeline.
  - All links forward different packets in parallel
- Throughput is determined by the slowest stage.
  - Called the bottleneck link
- Does not really matter why the link is slow.
  - Low link bandwidth
  - Many users sharing the link bandwidth



Network Service Models

- Set of services that the network provides.
- Best effort service: network will do an honest effort to deliver the packets to the destination.
  - Usually works
- “Guaranteed” services.
  - Network offers (mathematical) performance guarantees
  - Can apply to bandwidth, latency, packet loss, ..
- “Preferential” services.
  - Network gives preferential treatment to some packets
  - E.g. lower queuing delay
- Quality of Service is closely related to the question of fairness.

Cookies: Keeping “state”

Many major Web sites use cookies

Four components:

1) Cookie header line in the HTTP response message
2) Cookie header line in HTTP request message
3) Cookie file kept on user’s host and managed by user’s browser
4) Back-end database at Web site

Example:

- Susan accesses Internet always from same PC
- She visits a specific e-commerce site for the first time
- When initial HTTP requests arrives at site, site creates a unique ID and creates an entry in backend database for ID

Persistent HTTP

Nonpersistent HTTP issues:

- Requires 2 RTTs per object
- OS must work and allocate host resources for each TCP connection
- But browsers often open parallel TCP connections to fetch referenced objects

Persistent HTTP

- Server leaves connection open after sending response
- Subsequent HTTP messages between same client/server are sent over connection

Persistent without pipelining:

- Client issues new request only when previous response has been received
- One RTT for each referenced object

Persistent with pipelining:

- Default in HTTP/1.1
- Client sends requests as soon as it encounters a referenced object
- As little as one RTT for all the referenced objects

Persistent Connection Performance

- Benefits greatest for small objects
  - Up to 2x improvement in response time
- Server resource utilization reduced due to fewer connection establishments and fewer active connections
- TCP behavior improved
  - Longer connections help adaptation to available bandwidth
  - Larger congestion window improves loss recovery

Remaining Problems

- Serialized transmission
  - Much of the useful information in first few bytes
    - May be better to get the 1st 1/4 of all images than one complete image (e.g., progressive JPEG)
  - Can “packetize” transfer over TCP
    - Could use range requests
- Application specific solution to transport protocol problems ☹
  - Solve the problem at the transport layer
  - Could fix TCP so it works well with multiple simultaneous connections
    - More difficult to deploy