Accessing the Network

CS439: Principles of Computer Systems

April 15, 2015

Last Time

- Introduction to Networks
  - SAN, LAN, WAN
- OSI Model (7 layers)
  - Layer 1: hardware
  - Layer 2: Ethernet (frames)
    - hardware to hardware
    - ARP, MAC addresses
  - Layer 3: IP (packets)
    - sending machine to receiving machine
    - DNS, IP addresses
  - Layer 4: TCP, UDP (segments)
    - Sending process to receiving process
    - Ports
  - Layers 5, 6: OS stuff
  - Layer 7: Application (soon)
- Network communication
  - Protocols, naming, routing
- TCP/IP congestion control mechanisms

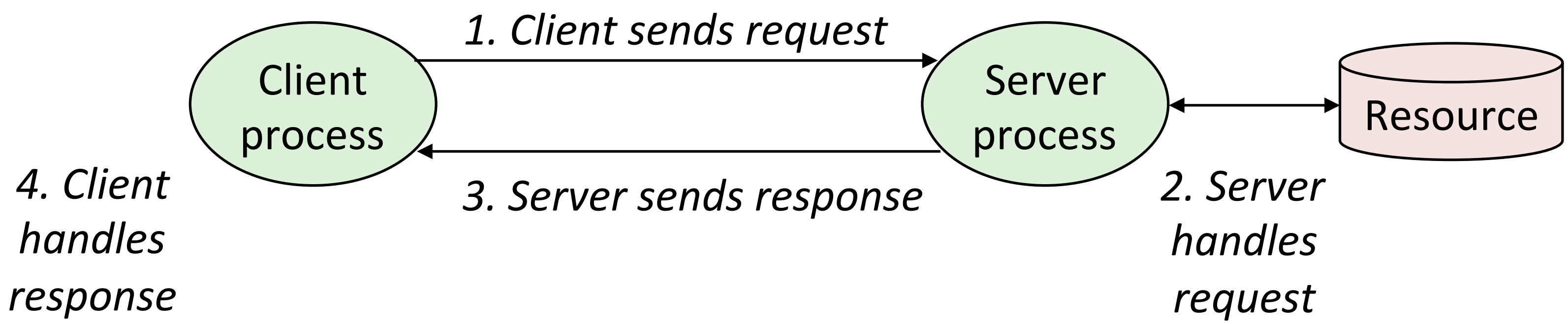
Today's Agenda

Accessing the Network

- Client-Server Transactions
- Ports
- Sockets
    - Client-Side Programming
    - Server-Side Programming
- Remote Procedure Calls (RPC)

Accessing the TCP/IP Family From User Code

A Client-Server Transaction



Note: clients and servers are processes running on hosts (can be the same or different hosts)

Most network applications are based on the client-server model:

- A *server* process and one or more *client* processes
- Server manages some *resource*
- Server provides *service* by manipulating resource for clients
- Server activated by request from client

A Client-Server Transaction: Plain Text

- Most network applications are based on the client-server model:
  - A server process and one or more client processes
  - Server manages some resource
  - Server provides service by manipulating resource for clients
  - Server activated by request from client
- Steps to Transaction
  - 1. Client sends request
  - 2. Server handles request, server process is connected to resource
  - 3. server sends response
  - 4. client handles response

Clients

- Examples of client programs
  - Web browsers, `ftp`, `telnet`, `ssh`

- How does a client find the server?
  - The IP address in the server socket address identifies the host (more precisely, an adapter on the host)
  - The (well-known) port in the server socket address identifies the service, and thus implicitly identifies the server process that performs that service.

Servers

- Servers are long-running processes (daemons)
  - Often created at boot-time by the init process
  - Typically run continuously until the machine is turned off
- Each server waits for requests to arrive on a well-known port associated with a particular service
- A machine that runs a server process is also often referred to as a “server”

Server Examples

- Web server
  - Resource: files/compute cycles (CGI programs)
  - Service: retrieves files and runs CGI programs on behalf of the client

- FTP server
  - Resource: files
  - Service: stores and retrieve files

- Telnet server
  - Resource: terminal
  - Service: proxies a terminal on the server machine

- Mail server
  - Resource: email “spool” file
  - Service: stores mail messages in spool file

Well-Known (TCP) Ports

- Port 21: FTP
- Port 22: SSH
- Port 23: Telnet
- Port 25: SMTP (Email)
- Port 79: Finger
- Port 80: Web

See `/etc/services` for a comprehensive list of the port mappings on a Linux machine

Well-Known (TCP) Ports: Plain Text

- Port 21: FTP
- Port 22: SSH
- Port 23: Telnet
- Port 25: SMTP (Email)
- Port 79: Finger
- Port 80: Web
- See /etc/services for a comprehensive list of the port mappings on a Linux machine

Fine, But….

Hurry up! We *still* don't know how to use them!

So…

How do we *USE* them?

…

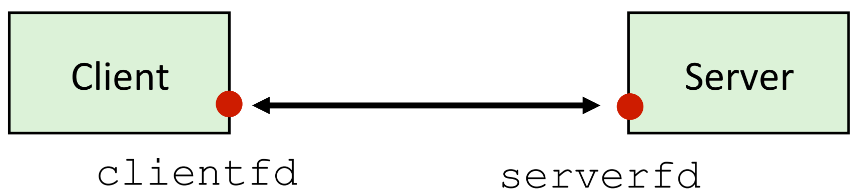
Funny you should ask….

Sockets!

- Created in the early 80s as a part of the original Berkeley distribution of UNIX that contained an early version of the Internet protocols
- Underlying basis for all Internet applications
- Based on the client/server programming model

What is a Socket?

- To the kernel, a socket is an endpoint of communication
- To an application, a socket is a file descriptor that lets the application read/write from/to the network
  - Remember: All Unix I/O devices, including networks, are modeled as files
- Clients and servers communicate with each other by reading from and writing to socket descriptors



- The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors

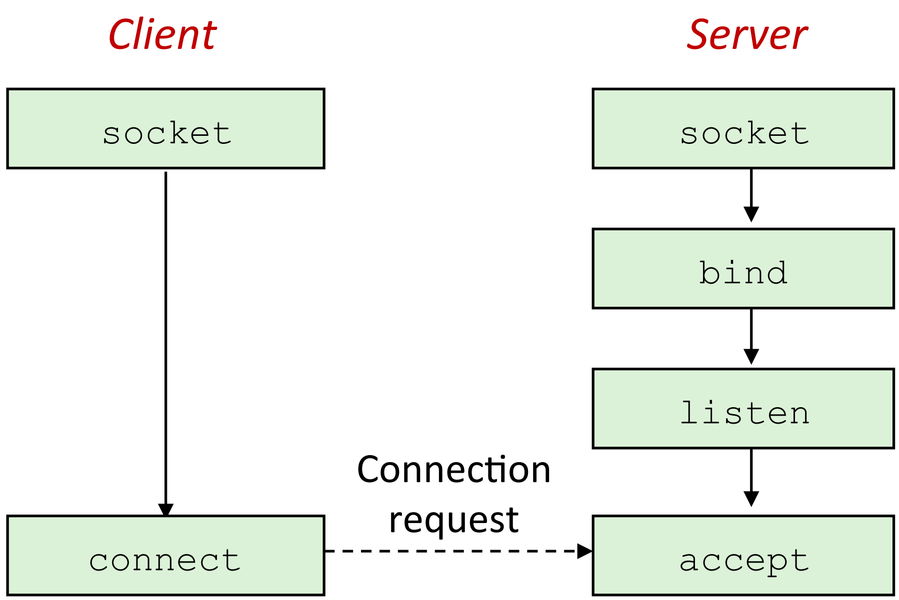
What is a Socket?: Plain Text

- To the kernel, a socket is an endpoint of communication
- To an application, a socket is a file descriptor that lets the application read/write from/to the network
  - Remember: all Unix I/O devices, including networks, are modeled as files
- Clients and servers communicate with each other by reading from and writing to socket descriptors
  - Client and server each have their own file descriptor
- The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors

Internet Connections

- Clients and servers communicate by sending streams of bytes over connections:
  - Point-to-point, full-duplex (2-way communication), and reliable.
- A socket is an endpoint of a connection
  - Socket address is an IPaddress:port pair
- A port is a 16-bit integer that identifies a process:
  - *Well-known* port: Associated with some service provided by a server (e.g., port 80 is associated with Web servers)
  - *Ephemeral* port: Assigned automatically on client when client makes a connection request
- A connection is uniquely identified by the socket addresses of its endpoints (socket pair)
  - (client_addr:client_port, server_addr:server_port)

Overview of the Sockets Interface



Overview of the Sockets Interface: Text Description

- Client executes the commands:
  - socket, and
  - connect: sends a connection request
- Server executes the commands:
  - socket,
  - bind,
  - listen, and
  - accept: accepts the connection request

Client: `socket(2)`

`socket(2)` creates a socket descriptor on the client

- Allocates and initializes some internal data structures
- `AF_INET`: indicates that the socket is associated with Internet protocols
- `SOCK_STREAM`: selects a reliable byte stream connection
  - Bi-directional pipes
  - Gives you TCP
  - `SOCK_DGRAM` results in UDP

```
int clientfd;  /* socket descriptor */

if ((clientfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
    return -1; /* check errno for cause of error */

...
```

Client: `socket(2)` Plain Text

- socket(2) creates a socket descriptor on the client
  - Allocates and initializes some internal data structures
  - AF_INET: indicates that the socket is associated with Internet protocols
  - SOCK_STREAM: selects a reliable byte stream connection
    - Bi-directional pipes
    - Gives you TCP
    - SOCK_DGRAM results in UDP
- Code:

```
int clientfd; /*socket descriptor*/
if ((clientfd = socket (AF_INET, SOCK_STREAM, 0)) < 0)
    return -1; /* check errno for cause of error*/
```

Client: Find Server Using DNS

The client then builds the server’s Internet address

```
int clientfd;                     /* socket descriptor */
struct hostent *hp;               /* DNS host entry */
struct sockaddr_in serveraddr; /* server’s IP address */

...

/* fill in the server's IP address and port */
if ((hp = gethostbyname(hostname)) == NULL)
    return -2; /* check h_errno for cause of error */
bzero((char *) &serveraddr, sizeof(serveraddr));
serveraddr.sin_family = AF_INET;
serveraddr.sin_port = htons(port);
serveraddr.sin_addr.s_addr=htonl(hp->h_addr_list[0]);
```

Note: This is untested code.

Client: Find Server Using DNS Plain Text

- The client then builds the server’s internet address
- Code:

```
int client fd; /*socket descriptor*/
struct hostent *hp; /*DNS host entry*/
struct sockaddr_in serveraddr; /*server’s IP address*/
…
/* fill in the server’s IP address and port */
if ((hp = gethostbyname(hostname)) == NULL)
        return -2; /*check h_errno for cause of error */
bzero((char *) &serveraddr, sizeof(serveraddr));
serveraddr.sin_family = AF_INET;
serveraddr.sin_port = htons(port);
serveraddr.sin_addr.s_addr = hton1(hp->h_addr_list[0]);
```

- Note: This is untested code.

Client: `connect()`

Finally the client creates a connection with the server

- Client process blocks until the connection is created
- After resuming, the client is ready to begin exchanging messages with the server via Unix I/O calls (typically send/recv) on descriptor `clientfd`

```
int clientfd;                           /* socket descriptor */
struct sockaddr_in serveraddr;          /* server address */
typedef struct sockaddr SA;             /* generic sockaddr */

...

/* Establish a connection with the server */
if (connect(clientfd, (SA *)&serveraddr, sizeof(serveraddr)) < 0)
  return -1;
```

Client: `connect()` Plain Text

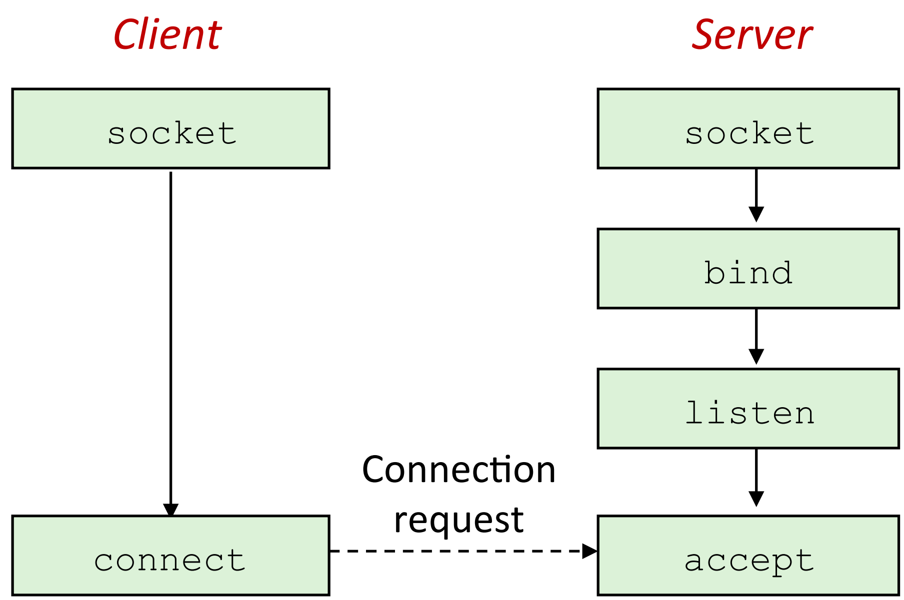
- Finally the client creates a connection with the server
  - Client process blocks until the connection is created
  - After resuming, the client is ready to being exchanging messages with the server via Unix I/O calls (typically send/recv) on descriptor clientfd
- Code:

```
int clientfd; /* socket descriptor */
struct sockaddr_in serveraddr; /* server address */
typedef struct sockaddr SA; /* generic sockaddr */

…

/* Establish a connection with the server */
if (connect(clientfd, (SA *)&serveraddr, sizeof(serveraddr)) < 0)
    return -1;
```

Overview of the Sockets Interface



Overview of the Sockets Interface: Text Description

- Client executes the commands:
  - socket, and
  - connect: sends a connection request
- Server executes the commands:
  - socket,
  - bind,
  - listen, and
  - accept: accepts the connection request

Server: `setsockopt(2)`

- Set up socket very similar to client, except…
- Give the socket some attributes

```
...
/* Eliminates "Address already in use" error from bind(). */
if (setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR,
               (const void *)&optval , sizeof(int)) < 0)
    return -1;
```

- Handy trick that allows us to rerun the server immediately after we kill it
  - Otherwise we would have to wait about 15 seconds
  - Eliminates "Address already in use" error from **`bind()`**
- Strongly suggest you do this for all your servers to simplify debugging

Server: `setsockopt(2)` Plain Text

- Set up socket very similar to client, except…
- Give the socket some attributes
- Code:

```
…
/* eliminates "address already in use" error from bind(). */
if (setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR, (const
void*)&optval, sizeof(int)) < 0)
	return -1;
```

- Handy trick that allows us to rerun the server immediately after we kill it
  – Otherwise we would have to wait about 15 seconds
  – Eliminates "address already in use" error from bind()
- Strongly suggest you do this for all your servers to simplify debugging

Server: `bind(2)`

`bind()` associates the socket with the socket address (created similarly to that of the client)

```
int listenfd;                    /* listening socket */
struct sockaddr_in serveraddr; /* server's socket addr */

...
  /* listenfd will be an endpoint for all requests to port
     on any IP address for this host */
  if (bind(listenfd, (SA *)&serveraddr, sizeof(serveraddr)) < 0)
      return -1;
```

Server: `bind(2)` Plain Text

- bind() associates the socket with the socket address (creates similarly to that of the client)
- Code:

```
int listen fd; /* listening socket */
struct sockaddr_in server addr; /*server’s socket addr */
…
/*listenfd will be an endpoint for all requests to port on
any IP address for this host */
if (bind(listenfd, (SA *)&serveraddr, sizeof(serveraddr))
< 0)
    return -1;
```

Server: `listen(2)`

- `listen()` indicates that this socket will accept connection (`connect`) requests from clients
- `LISTENQ` is a constant indicating how many pending requests allowed

```
int listenfd; /* listening socket */

...
 /* Make it a listening socket ready to accept connection requests */
    if (listen(listenfd, LISTENQ) < 0)
        return -1;
```

- We're finally ready to enter the main server loop that accepts and processes client connection requests.

Server: `listen(2)` Plain Text

- listen() indicates that this socket will accept connection (connect) requests from clients
- LISTENQ is a constant indicating how many pending requests allowed
- Code:

```
int listenfd; /* listening socket */
…
/* Make it a listening socket ready to accept connection
requests */
if (listen(listenfd, LISTENQ) < 0)
    return -1;
```

Server: `accept`

- `accept()` blocks waiting for a connection request

```
int listenfd; /* listening descriptor */
int connfd;   /* connected descriptor */
struct sockaddr_in clientaddr;
int clientlen;

clientlen = sizeof(clientaddr);
connfd = accept(listenfd, (SA *)&clientaddr, &clientlen);
```

- `accept()` returns a *connected descriptor* (`connfd`) with the same properties as the *listening descriptor* (`listenfd`)
  - Returns when the connection between client and server is created and ready for I/O transfers
  - All I/O with the client will be done via the connected socket
- `accept()` also fills in client's IP address

Server: `accept`

- accept() blocks waiting for a connection request
- Code:

```
int listenfd; /* listening descriptor */
int connfd; /*connected descriptor */
struct sockaddr_in clientaddr;
int clientlen;
clientlen = sizeof(clientaddr);
connfd = accept(listenfd, (SA *)&clientaddr, &clientlen);
```

- accept() returns a connected descriptor (connfd) with the same properties as the listening descriptor (listenfd)
  - Returns when the connection between client and server is created and ready for I/O transfers
  - All I/O with the client will be done via the connected socket
- accept() also fills in client's IP address

iClicker Question

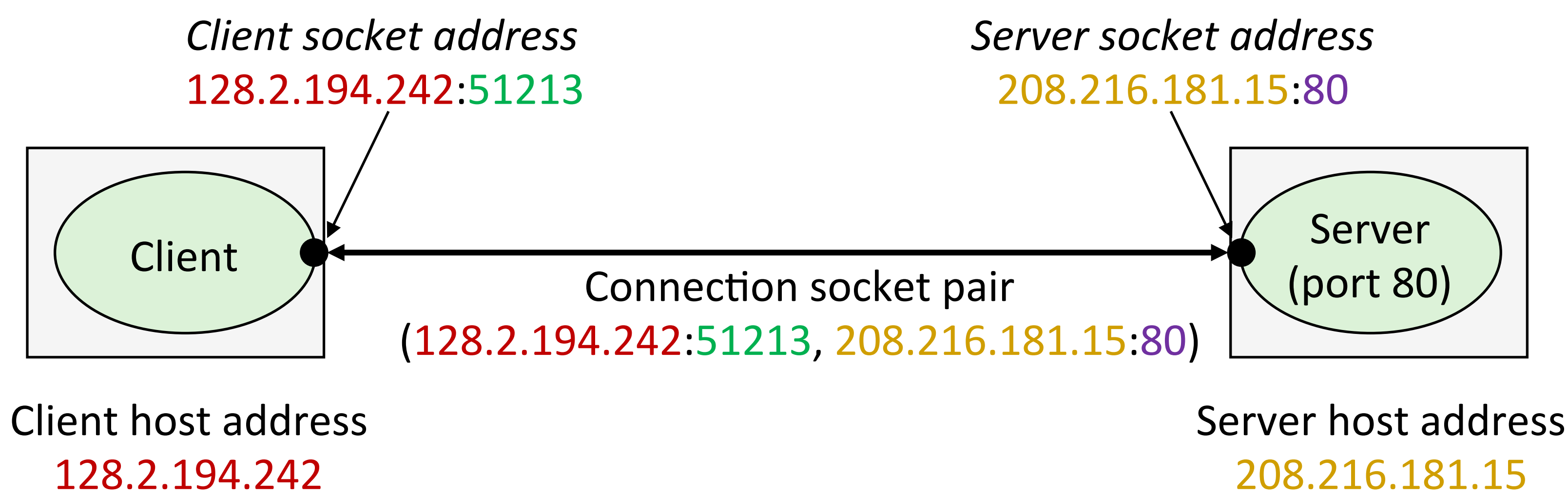
The listen() call is listening on a different port than the port a server will eventually use to send to a client.

A. True
B. False

Socket Implementation

- Each socket fd has associated socket structure with:
  - Send and receive buffers
  - Queues of incoming connections (on listen socket)
  - A *protocol control block* (PCB)
  - A *protocol handle*
- PCB contains protocol-specific information, such as:
  - Pointer to IP TCB with source/destination IP address and port
  - Information about received packets and position in stream
  - Information about unacknowledged sent packets
  - Information about timeouts
  - Information about connection state (setup/teardown)

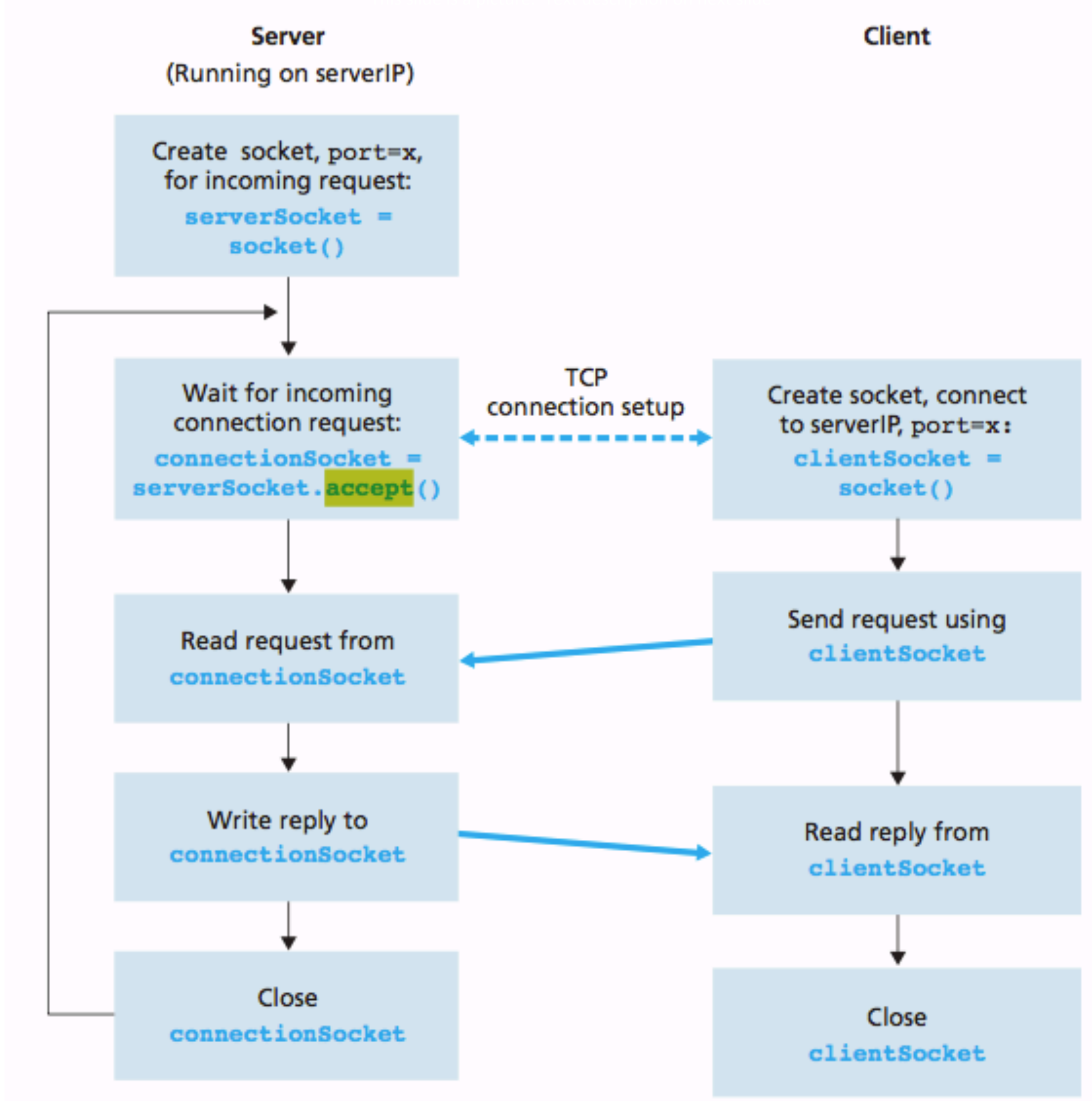
Putting It All Together: Anatomy of an Internet Connection



Putting It All Together: Anatomy of an Internet Connection Text Description

- The server and client each have a host address
  - Client host address: 128.2.194.242
  - Server host address: 208.216.181.15
- The server and client each have a socket address
  - Socket address is host address + port number
  - Client socket address: 128.2.194.242:51213
  - Server socket address: 208.216.181.15:80
- The client and server are connected by connection socket pair
  - Connection socket pair goes from client socket address to server socket address
  - 128.2.194.242:51213, 208.216.181.15:80

Overview of Connection Setup



Overview of Connection Setup: Text Description

- Server - running on serverIP
  1. Create socket, port=x, for incoming request: serverSocket = socket()
  2. Wait for incoming connection request: connectionSocket = serverSocket.accept()
     - This does TCP connection setup to connect to client side
  3. Read request from connectionSocket
     - Interacts with Client who sent the request here
  4. Write reply to connectionSocket
     - Interacts with Client here; client reads the reply
  5. Close connectionSocket
  6. Go back to step 2 and repeat
- Client
  1. Create socket, connect to serverIP, port=x: clientSocket = socket()
     - this does TCP connection setup to connect to Server side
  2. Send request using clientSocket
     - interacts with Server who reads the request
  3. Read reply from clientSocket
     - interacts with Server here; server wrote the reply
  4. Close clientSocket

Remote Procedure Calls

Also a Client/Server Model

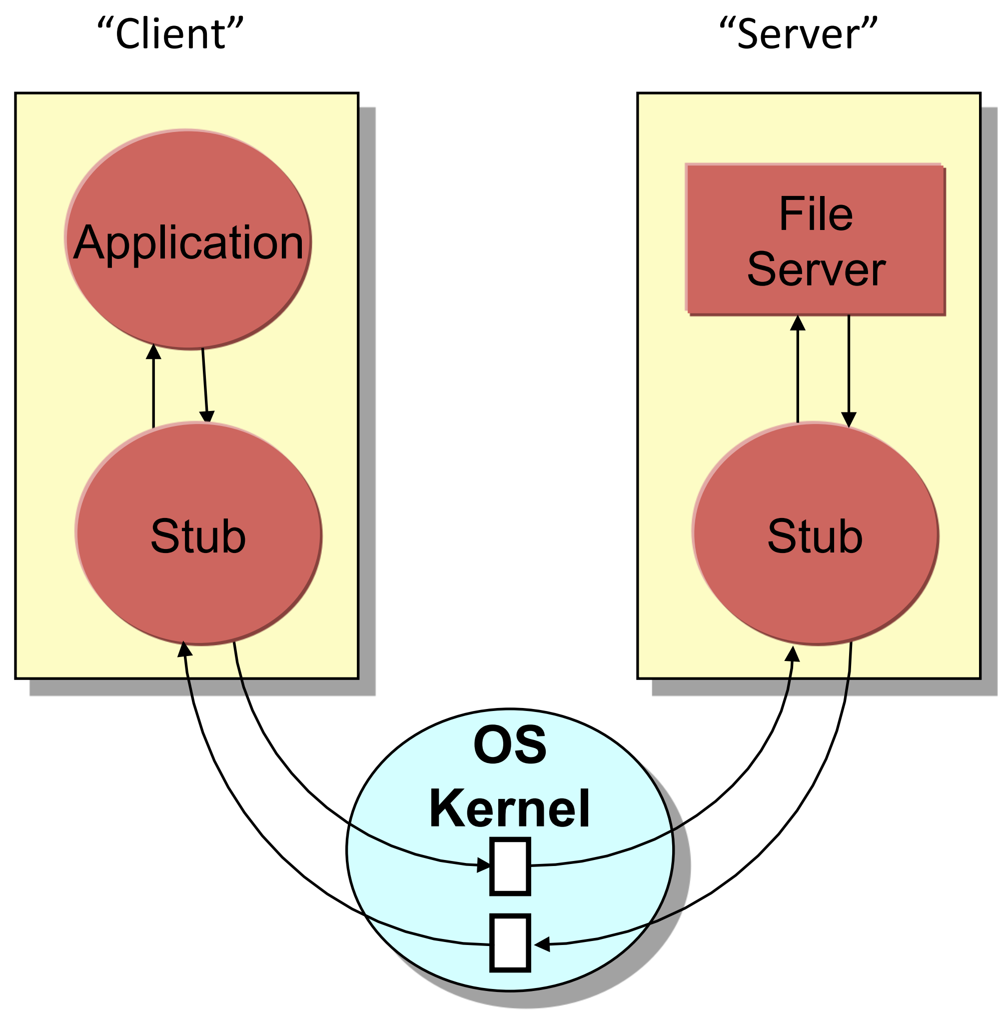
- One of the most common models for structuring network communication (and now distributed computation)
- A *server* is a process or collection of processes that provides a service
  - may exist on one or more nodes
- A *client* is a program that uses the service
  - first binds to the server (locates it in the network and establishes a connection)
  - then sends the server a request to perform some action
- Remote Procedure Calls is one common way this structure is implemented

Remote Procedure Calls (RPC)

- Servers export procedures for some set of clients to call
- To use the server, the client does a procedure call
- OS manages the communication
- Is *NOT* message passing!
  - message passing requires more work for the application, as we saw with TCP/IP and we'll see again next week

RPC: High-Level

- Remote procedure calls abstract out the *send-wait-reply* paradigm into a "procedure call"
- Remote procedure calls can be made to look like "local" procedure calls by using a *stub* that hides the details of remote communication



RPC: High-Level Plain Text

- Remote procedure calls abstract out the send-wait-reply paradigm into a “procedure call”
- Remote procedure calls can be made to look like “local” procedure calls by using a stub that hides the details of remote communication
- Communication example for single-machine RPC:
  - Client side:
    - Application calls client stub and client stub copies relevant data to kernel buffer
  - Server side:
    - Server stub copies information out of buffer and calls requested function in file server
    - File server receives information from server stub, performs function, and returns answer to server stub
    - Server stub copies answer to kernel buffer
  - Client side:
    - Client stub retrieves data from kernel buffer and returns it to application

RPC: Lower-Level

The RPC mechanism uses the procedure *signature* (number and type of arguments and return value)

1. to generate a client stub that bundles RPC arguments and sends them off to the server.
2. to generate the server stub that unpacks the message and makes the procedure call

The stubs actually do the work, and the client and server communicate through the stubs.

RPC: More Detail

```
process P1
begin
    :
    call Function(args)
    :
end P1
```

```
procedure Function(args)
begin
  <marshall parameters>
  send(FunctionServer,params)
  receive(FunctionServer,results)
  <unpack results>
  return(results)
end Function
```

```
procedure realFunction(args)
begin
      :
      :
    return(results)
end realFunction
```

```
process FunctionServer
begin
  loop
    sender := select()
    receive(sender,params)
    <unpack parameters>
    call realFunction(args)
    <marshall results>
    send(sender,results)
  end loop
end FunctionServer
```

Client

Network

Server

RPC: More Detail

1. Client, Process P1: begin … call Function(args) … end P2
2. Client stub:

```
procedure Function(args)
    begin
    <marshall parameters>
    send(FunctionServer params)
    receive(FunctionServer results)
    <unpack results>
    return(results)
end Function
```

3. network used to connect to the Server
4. Server stub, process FunctionServer

```
begin
    loop
    sender := select()
    receiver(sender params)
    <unpack parameters>
    call realFunction(args)
    <marshall results>
    send(sender results)
    end loop
end FunctionServer
```

5. Server, procedure realFunction(args): begin … return results … end realFunction

RPC and Regular Procedure Calls

Similarities between procedure call and RPC:

- Parameters ↔ request message
- Result ↔ reply message
- Name of procedure ↔ passed in request message
- Return address ↔ mailbox of the client

RPC is Not Message Passing

Regular client-server protocols involve sending data back and forth according to shared state

```
Client:                          Server:
HTTP/1.0 index.html GET
                                 200 OK
                                 Length: 2400
                                 (file data)
HTTP/1.0 hello.gif GET
                                 200 OK
                                 Length: 81494
                                 …
```

RPC is Not Message Passing: Plain Text

- Regular client-server protocols involve sending data back and forth according to shared state
- Example of message passing:
  - Client: HTTP/1.0 index.html GET
  - Server: 200 OK Length: 2400 (file data)
  - Client: HTTP/1.0 hello.gif GET
  - Server: 200 OK Length: 81494

RPC is Not Message Passing (II)

RPC servers will call arbitrary functions in dll, exe, with arguments passed over the network, and return values back over network

Client:	**Server:**
foo.dll,bar(4, 10, “hello”)	
	“returned_string”
foo.dll,baz(42)	
	err: no such function
…	

RPC is Not Message Passing (II): Plain Text

- RPC servers will call arbitrary functions in dll, exe, with arguments passed over the network, and return values back over network
- Client: foo.dll,bar(4, 10, “hello”)
- Server: “returned_string”
- Client: foo.dll,baz(42)
- Server: err: no such function

iClicker Question

Why does turning every file system operation into an RPC to a server perform poorly?

A. Disk latency is larger than network latency
B. Network latency is larger than disk latency
C. No server-side cache
D. No client-side cache

Problems with RPC

- Failure handling
  - A program may hang because of
    - Failure of a remote machine; or
    - Failure of the server application on the remote machine
  - An inherent problem with distributed systems, not just RPC
    - Lamport: “A distributed system is one where you can’t do work because some machine that you have never heard of has crashed”
- Performance
  - Cost of procedure call << same machine RPC << network RPC

More Insidious Problems with RPC

- Cannot pass pointers
  - call by reference becomes copy-restore (but might fail)
- Weakly typed languages
  - client stub cannot determine size
- Not always possible to determine parameter types
- Cannot use global variables
  - may get moved to remote machine

Summary

- Remote procedure calls enable a client to perform computation on a server
- Support is provided somewhere other than the application (may be language, may be OS)
- RPC is really useful for harnessing power of distributed computation
- RPC can have some drawbacks---particularly if you are not aware you are executing an RPC

Announcements

- Exams are mostly graded, scores are not entered
  - Will be returned in discussion section this week
- Project 3 due Friday, 4/17
- Project 4 out Friday
  - Will discuss in discussion section NEXT week
- Homework 9 is posted and due Friday 8:45a