# SC250
# Computer Networking I

# Socket Programming

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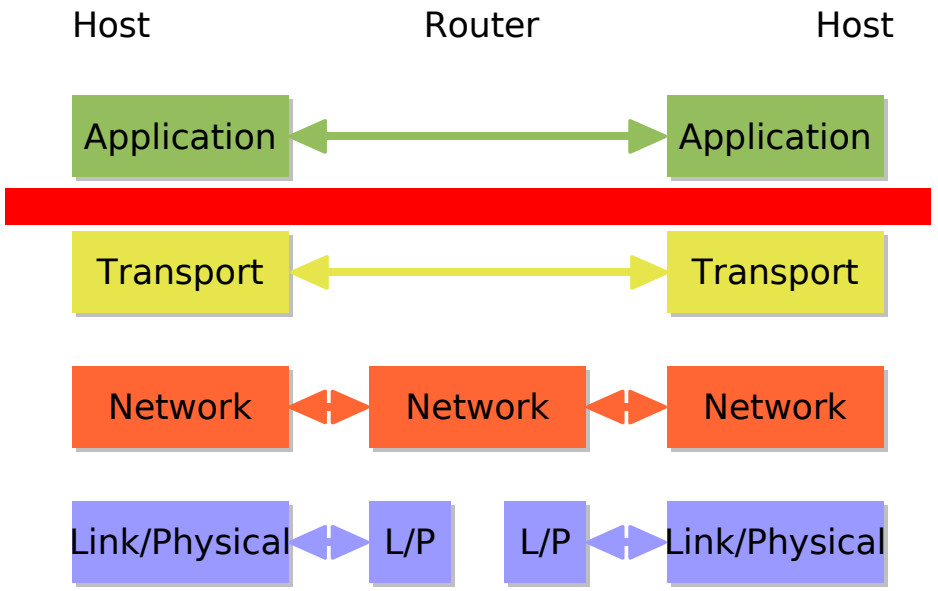
# Today's Objectives

- Transport layer service through sockets
  - Multiplexing-demultiplexing:
    - How to make sure that multiple processes on a single machine can communicate concurrently without interfering with each other?
- Java sockets
  - stream sockets (TCP)
  - stream example
  - datagram sockets (UDP)
  - datagram example
- Multi-threaded servers
- Socket programming in C



# Transport vs. Network Layer

- Network layer:
  - logical communication between hosts (IP to IP)
- Transport layer:
  - logical communication between processes (IP+port to IP+port)
  - relies on + enhances network layer services

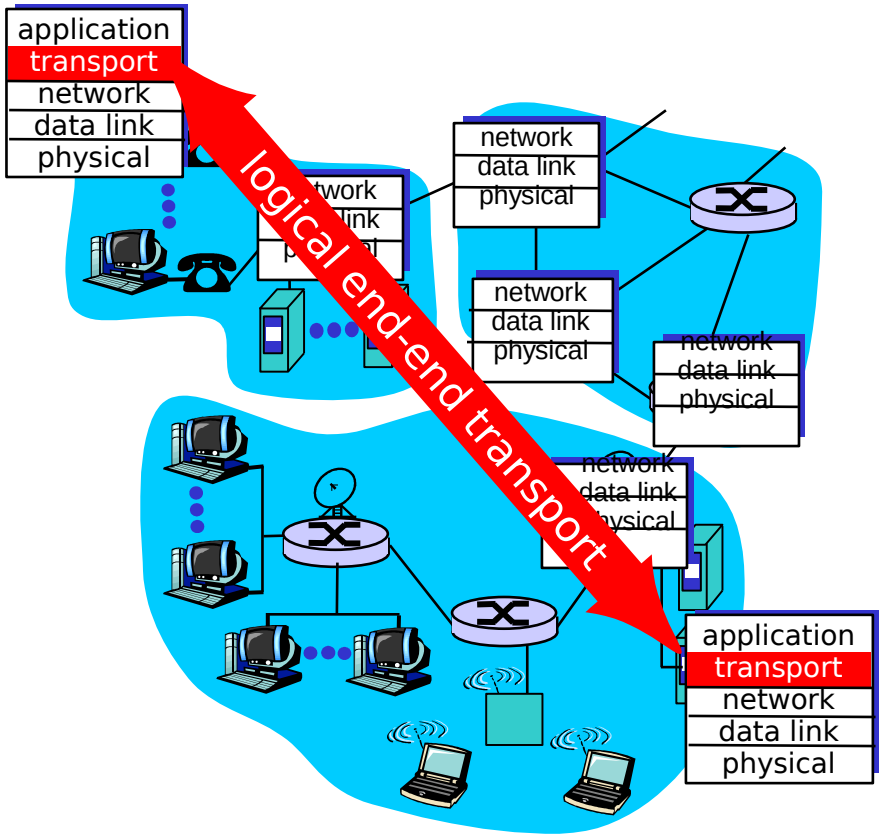
Household analogy:

*12 kids sending letters to 12 kids*

- processes = kids
- app messages = letters in envelopes
- hosts = houses
- transport protocol = Ann and Bill handling all mail in each house
- network-layer protocol = postal service

# Internet Transport-Layer Protocols

- Reliable, in-order delivery: TCP
  - congestion control
  - flow control
  - connection setup
- Unreliable, unordered delivery: UDP
  - no-frills extension of “best-effort” IP
- Services not available:
  - delay guarantees
  - bandwidth guarantees



# Multiplexing/Demultiplexing

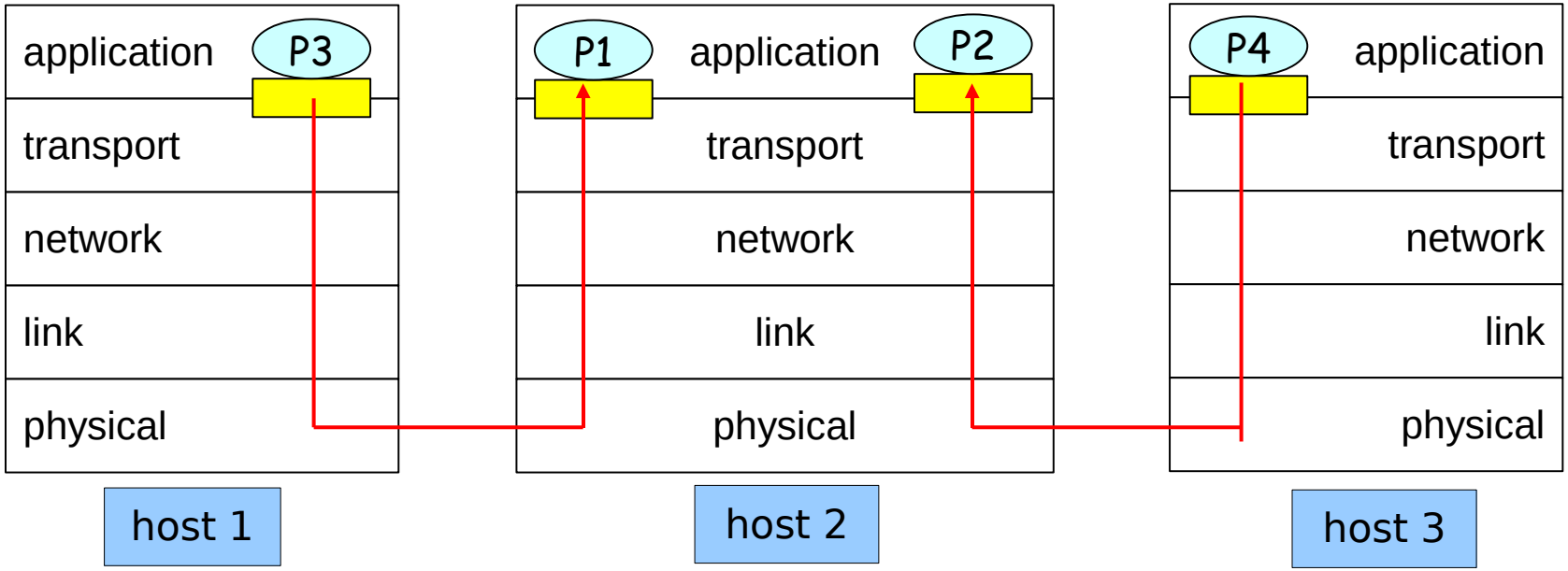
## Demultiplexing at rcv host:

delivering received segments to correct socket

## Multiplexing at send host:

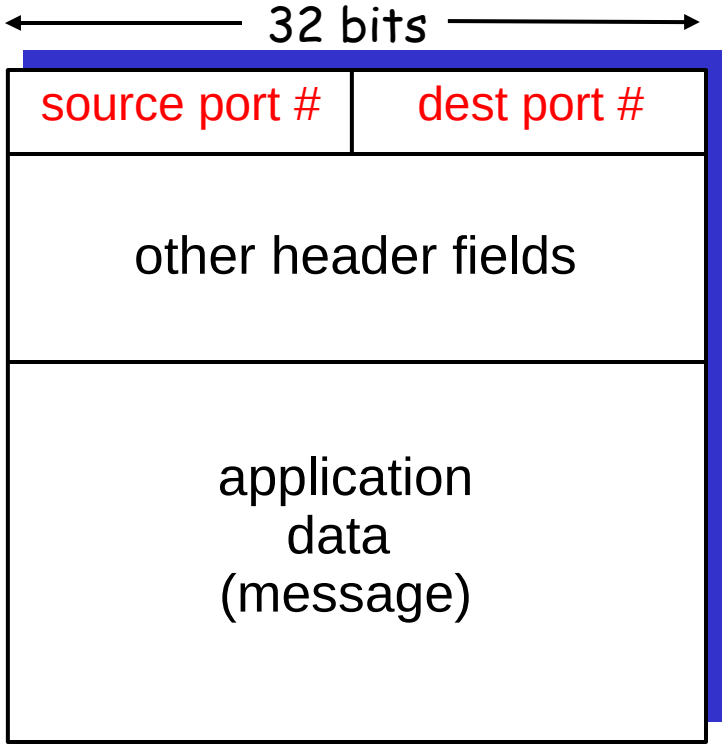
gathering data from multiple sockets, enveloping data with header (later used for demultiplexing)

= socket = process



# How Demultiplexing Works

- Host receives IP datagrams
  - each datagram has source IP address, destination IP address
  - each datagram carries 1 transport-layer segment
  - each segment has source, destination port number (recall: well-known port numbers for specific applications)
- Host uses IP addresses & port numbers to direct segment to appropriate socket




TCP/UDP segment format

# Connectionless Demultiplexing

- Create sockets with port numbers:

```
DatagramSocket mySocket1 = new
   DatagramSocket(99111);
DatagramSocket mySocket2 = new
   DatagramSocket(99222);
```

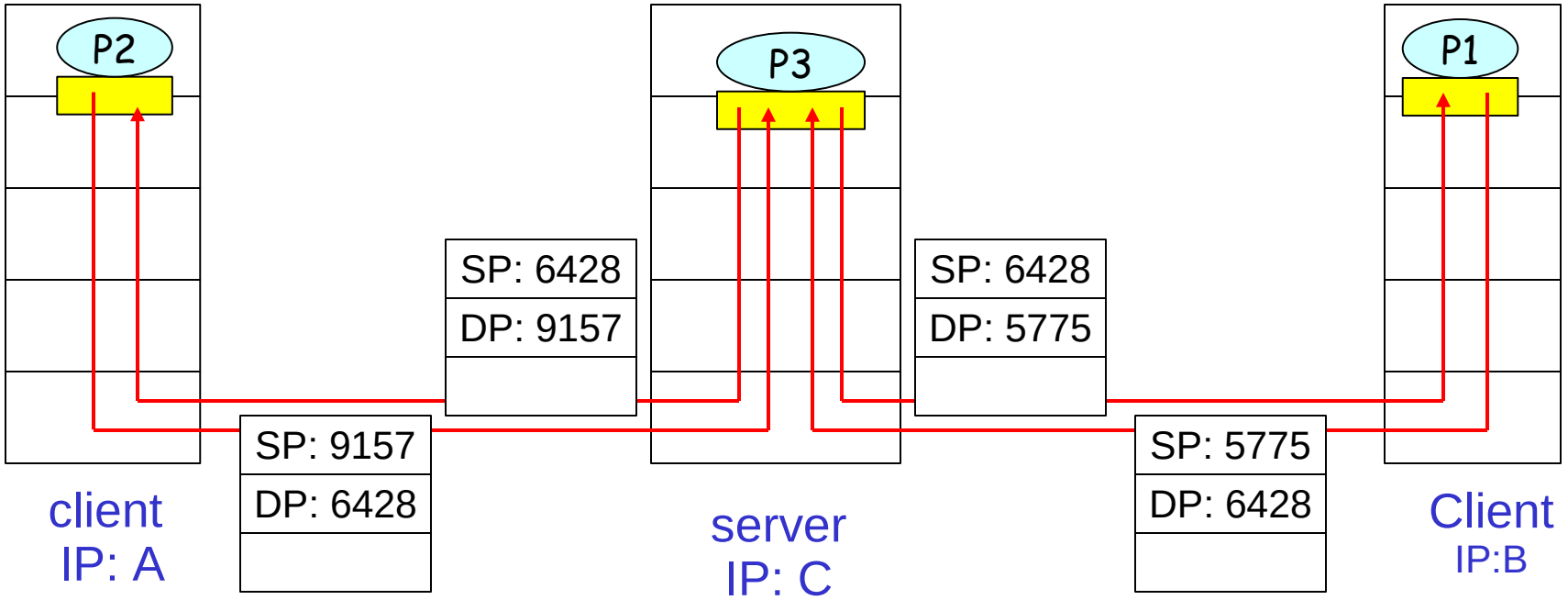
- UDP socket identified by two-tuple:

(dest IP address, dest port number)

- When host receives UDP segment:
  - checks destination port number in segment
  - directs UDP segment to socket with that port number
- IP datagrams with different source IP addresses and/or source port numbers directed to same socket

# Connectionless Demultiplexing (cont)

DatagramSocket serverSocket = new DatagramSocket(6428);

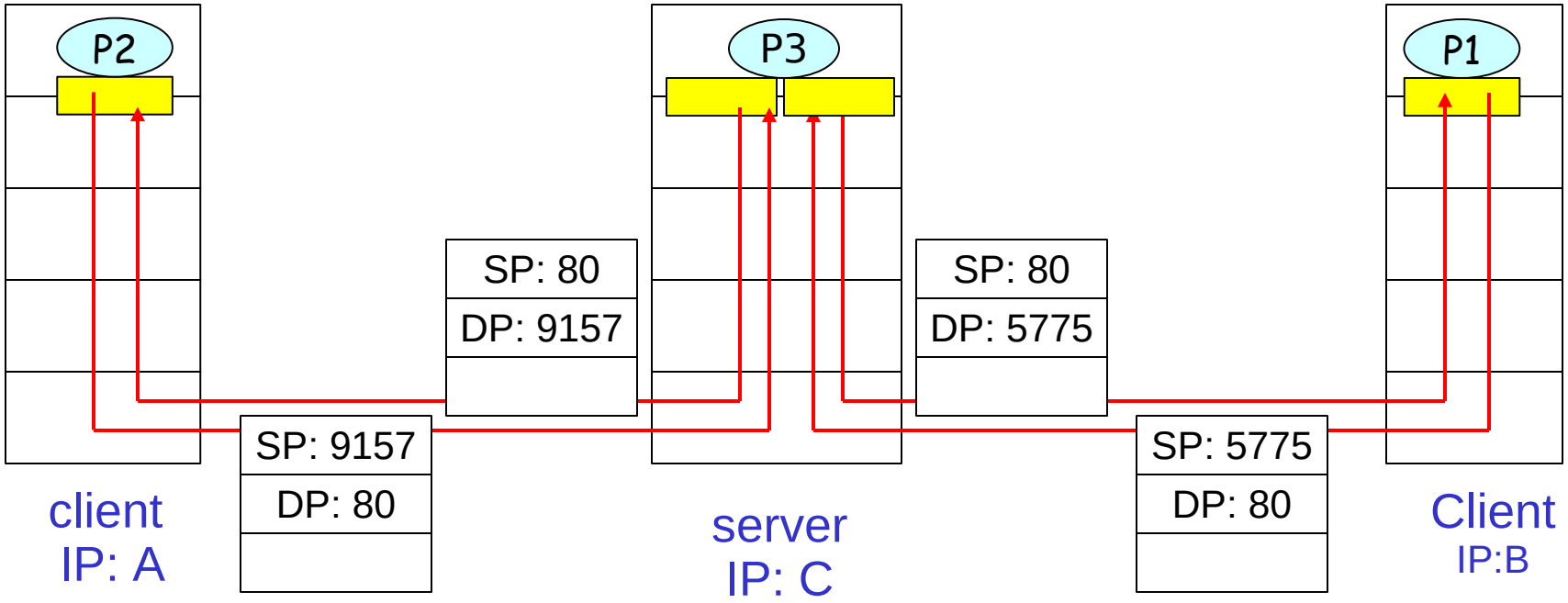



SP provides “return address”

# Connection-Oriented Demultiplexing

- TCP socket identified by 4-tuple:
  - source IP address
  - source port number
  - dest IP address
  - dest port number
- Recv host uses all four values to direct segment to appropriate socket
- Server host may support many simultaneous TCP sockets:
  - each socket identified by its own 4-tuple
- Web servers have different sockets for each connecting client
  - non-persistent HTTP will have different socket for each request

# Connection-Oriented Demux (cont)



# Network API: Sockets

- Application Programming Interface (API) provides a set of function types, data structures and constants
  - flexible, simple to use, standardized
- API to access transport protocols of the operating system is called a **socket**
  - Gives a file-system-like abstraction to the services of the transport protocols (open, close, read, write)
  - BSD sockets (introduced in BSD 4.1 Unix in 1981) are the most popular Internet sockets: FreeBSD, Linux, Windows, Mac OS X, ...
  - Sockets also used for other purposes (e.g., Unix interprocess communication)

# Client/Server Paradigm

- Network applications typically have two components:
  - Client:
    - initiates contact with the server
    - typically requests service from the server
  - Server:
    - passively listens for clients to connect (on a given port)
    - server process usually running all the time
- Applications implementing protocol standard
  - use well-known ports and adhere to standard (RFC)
- Proprietary protocol
  - complete control over design but should not use well-known port numbers

# Socket Programming with TCP

- Client must contact server
- server process must first be running
- server must have created socket (door) that welcomes client's contact
- Client contacts server by:
- creating client-local TCP socket
- specifying IP address, port number of server process

- When client creates socket: client TCP establishes connection to server TCP
- When contacted by client, server TCP creates new socket for server process to communicate with client
  - allows server to talk with multiple clients

application viewpoint

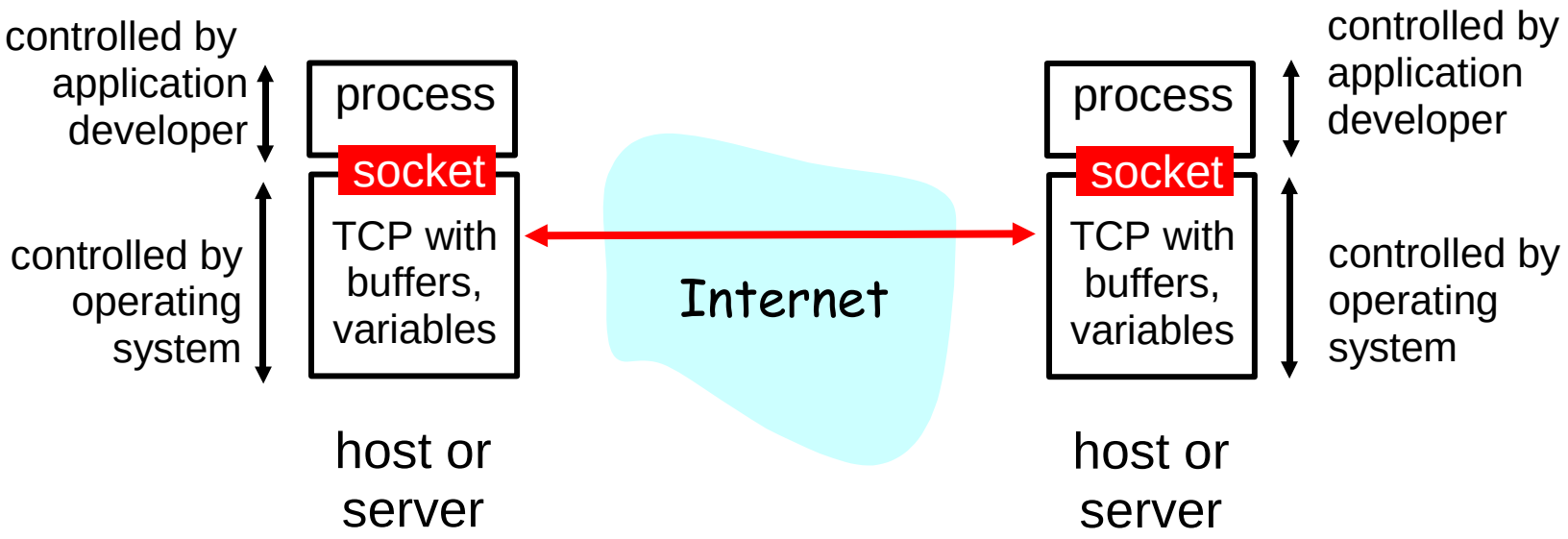
*TCP provides reliable, in-order transfer of bytes ("pipe") between client and server*

# TCP Socket Class

- Used for both client and server
- New socket is created using a Socket() constructor
- 4 constructors + 2 protected
- Connect with creation

java.lang.Object
|
+--java.net.Socket

public class **Socket**
extends Object

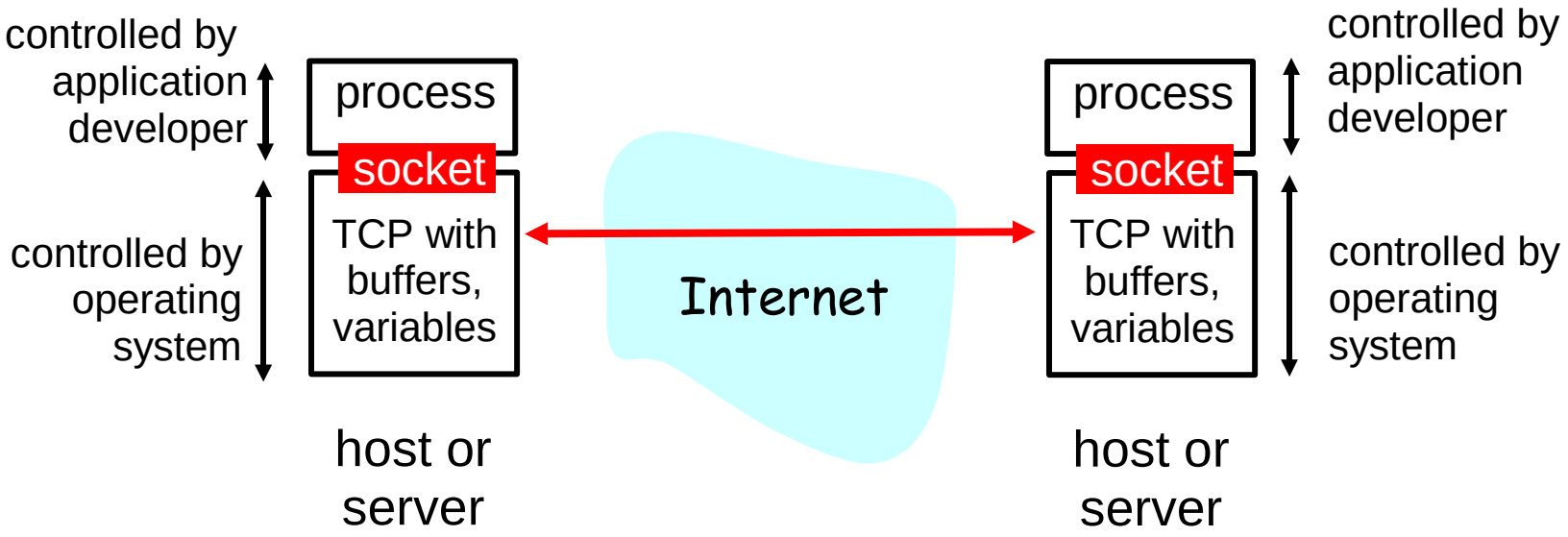


# TCP ServerSocket Class

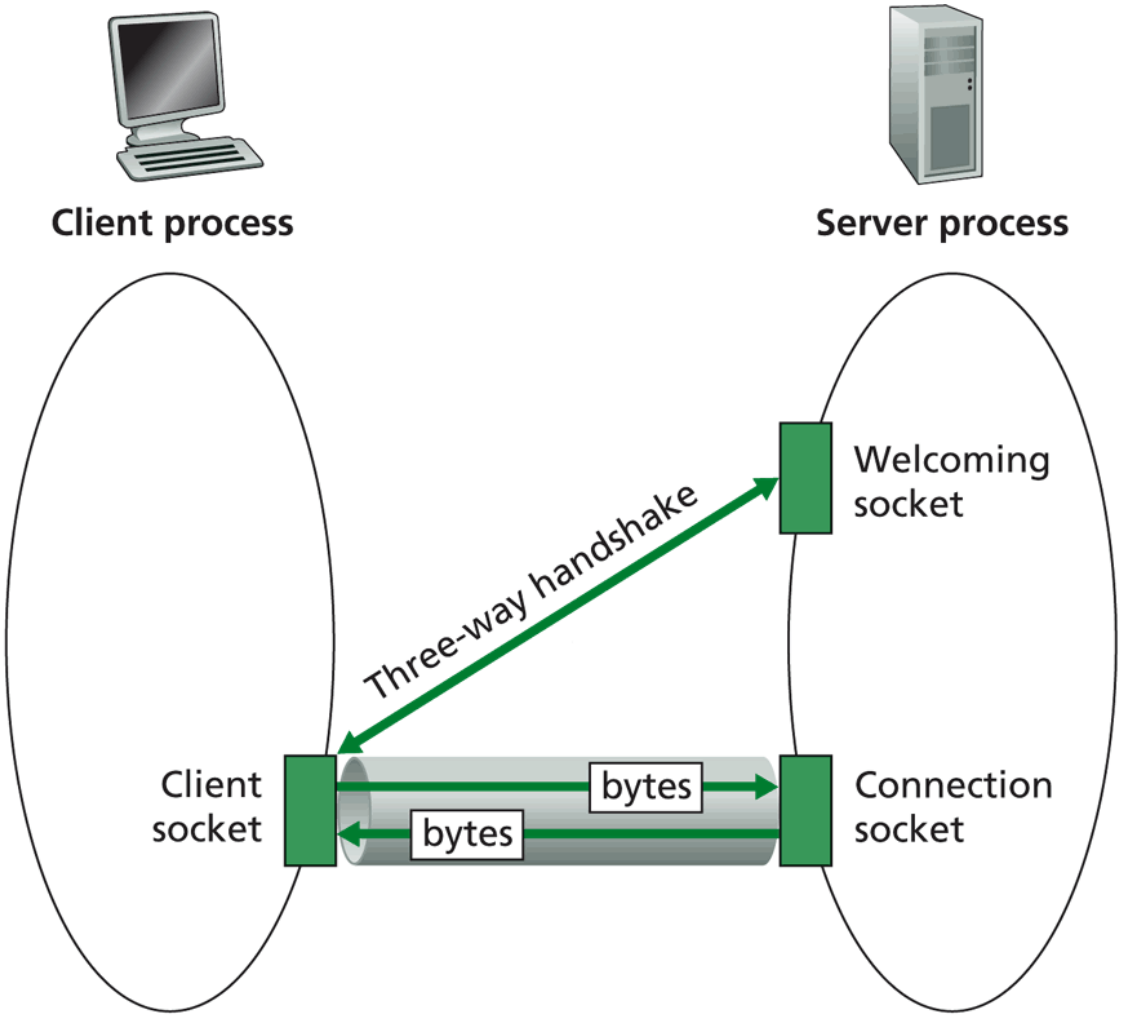
- Used for server
- New socket is created using a ServerSocket() constructor
- 3 constructors
- Buffers incoming connection requests (SYNs)
- Use accept() to get the next connection

java.lang.Object
|
+--java.net.ServerSocket

public class **ServerSocket**
extends Object



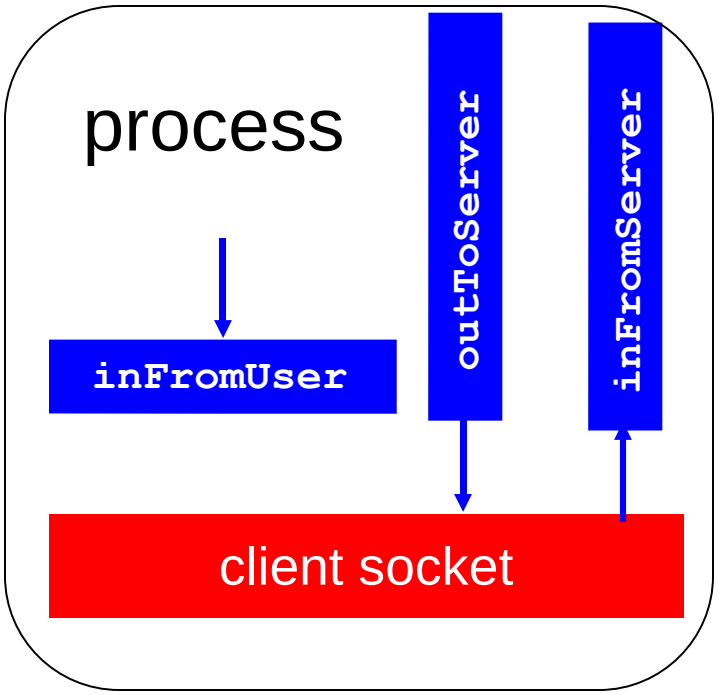
# TCP: Welcoming and Connection Sockets



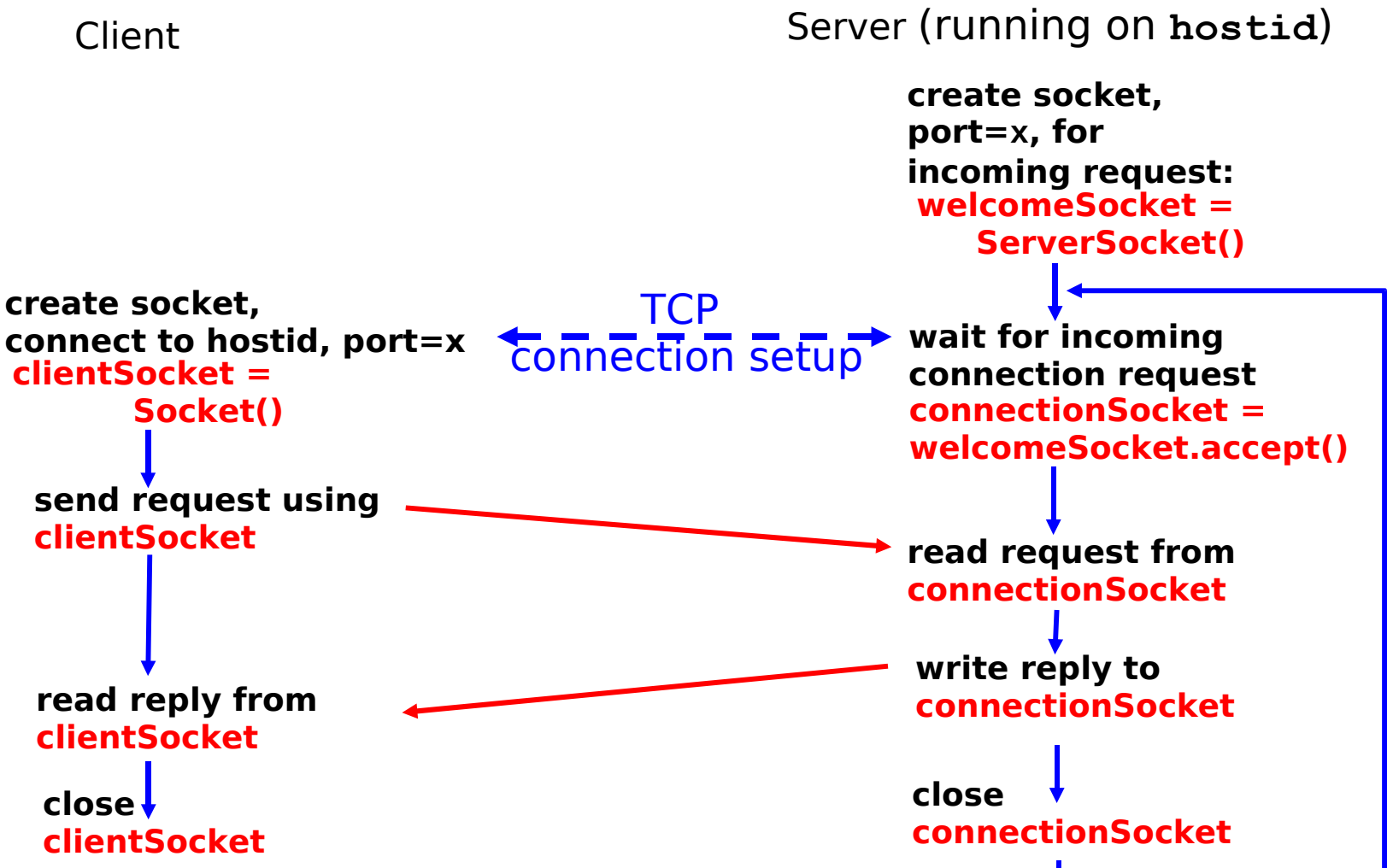
# Socket Programming with TCP

- Example client-server app:
- client reads line from standard input (**`inFromUser`** stream), sends to server via socket (**`outToServer`** stream)
- server reads line from socket
- server converts line to uppercase, sends back to client
- client reads, prints modified line from socket (**`inFromServer`** stream)

- Input stream: sequence of bytes into process
- Output stream: sequence of bytes out of process



# Client/Server Socket Interaction: TCP



# Example: Java Client (TCP)

```
import java.io.*;
import java.net.*;

class TCPClient {

    public static void main(String argv[]) throws Exception
    {
        String sentence;
        String modifiedSentence;
```

Create input stream

```
BufferedReader inFromUser =
  new BufferedReader(new InputStreamReader(System.in));
```

Create client socket, connect to server

```
Socket clientSocket = new Socket("hostname", 6789);
```

Create output stream attached to socket

```
DataOutputStream outToServer =
  new DataOutputStream(clientSocket.getOutputStream());
```

# Example: Java Client (TCP)

Create input stream attached to socket

```
BufferedReader inFromServer =
        new BufferedReader(new
InputStreamReader(clientSocket.getInputStream()));

  sentence = inFromUser.readLine();
```

aaaa

Send line to server

```
  outToServer.writeBytes(sentence + '\n');
```

Read line from server

```
  modifiedSentence = inFromServer.readLine();
```

AAAA

```
  System.out.println("FROM SERVER: " +
                                modifiedSentence);

  clientSocket.close();

  }
}
```

# Example: Java Server (TCP)


```
import java.io.*;
import java.net.*;

class TCPServer {

  public static void main(String argv[]) throws Exception
    {
      String clientSentence;
      String capitalizedSentence;

      ServerSocket welcomeSocket = new ServerSocket(6789);

      while(true) {
          Socket connectionSocket = welcomeSocket.accept();

          BufferedReader inFromClient =
            new BufferedReader(new
            InputStreamReader(
                    connectionSocket.getInputStream()));
```

Create welcoming socket at port 6789

Wait on welcoming socket for contact by client

Create input stream, attached to socket

# Example: Java Server (TCP)

Create output stream, attached to socket

```
DataOutputStream  outToClient =
  new DataOutputStream(
        connectionSocket.getOutputStream());
```

Read in line from socket

```
clientSentence = inFromClient.readLine();          aaaa
```

```
capitalizedSentence = clientSentence.toUpperCase() + '\n';
```

Write out line to socket

```
outToClient.writeBytes(capitalizedSentence);       AAAA
}
    }
}
```

End of while loop, loop back and wait for another client connection

# Socket Programming with UDP

UDP: no "connection" between client and server

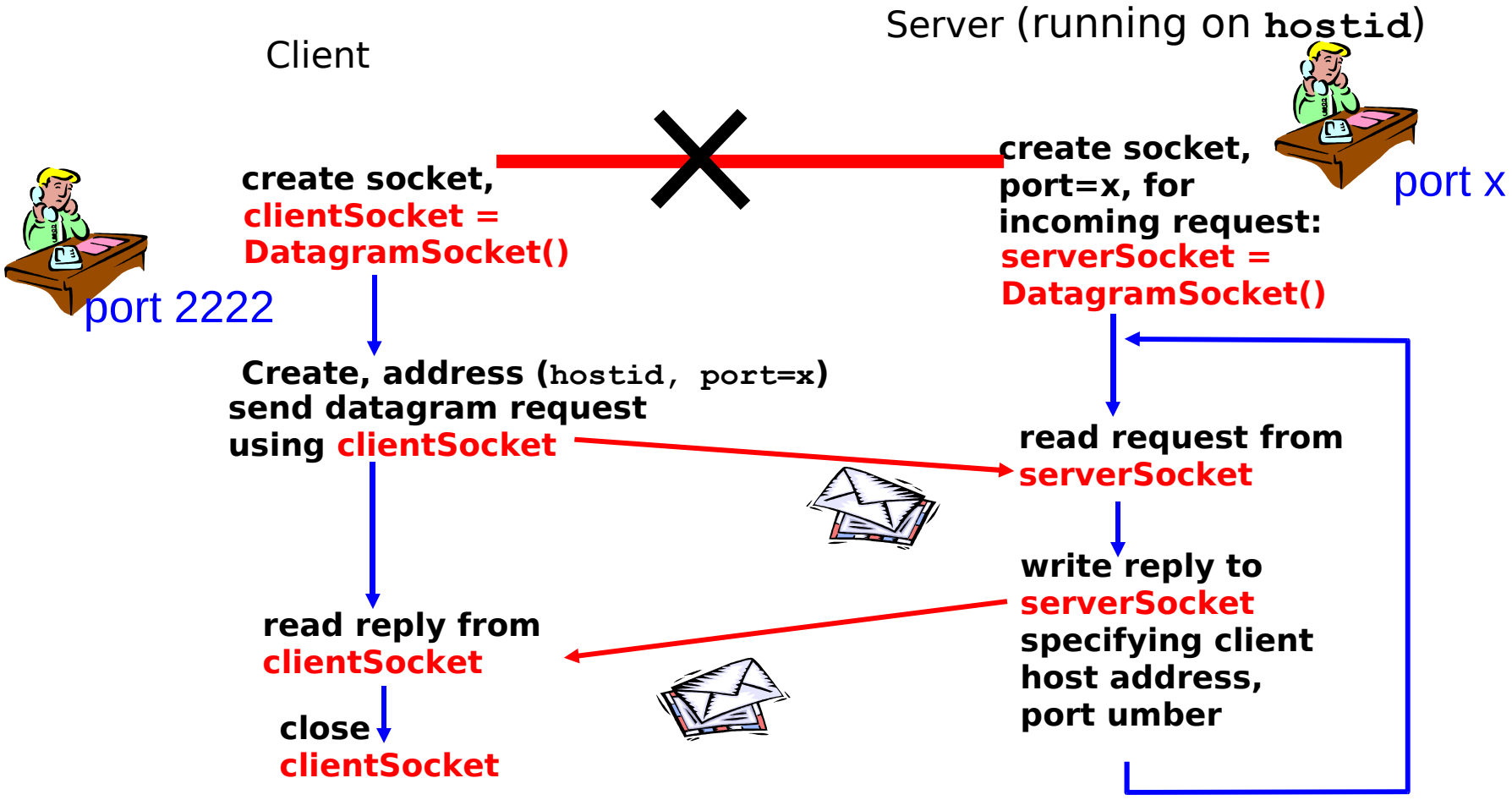
- no handshaking
- sender explicitly attaches IP address and port of destination
- receiver must extract IP address, port of sender from received datagram

UDP: transmitted data may be received out of order, or lost

application viewpoint

*UDP provides unreliable transfer of groups of bytes ("datagrams") between client and server*

# Client/Server Socket Interaction: UDP



# DatagramPacket Class

- Used for both client and server
- An independent message (datagram packet) is created using a DatagramPacket() constructor
- 4 constructors

java.lang.Object

|

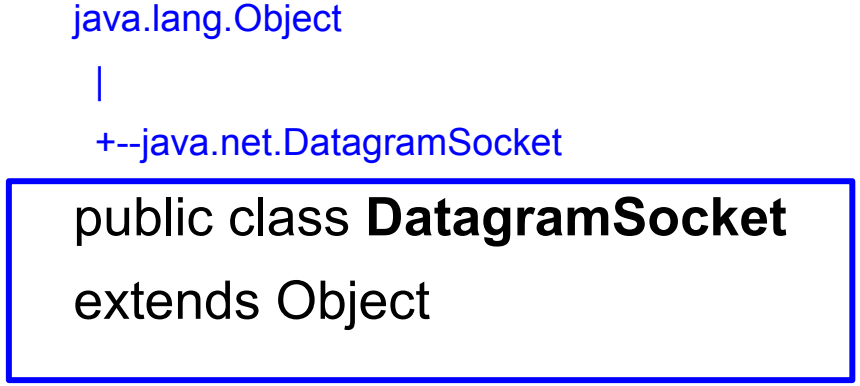
+--java.net.DatagramPacket

public final class **DatagramPacket**

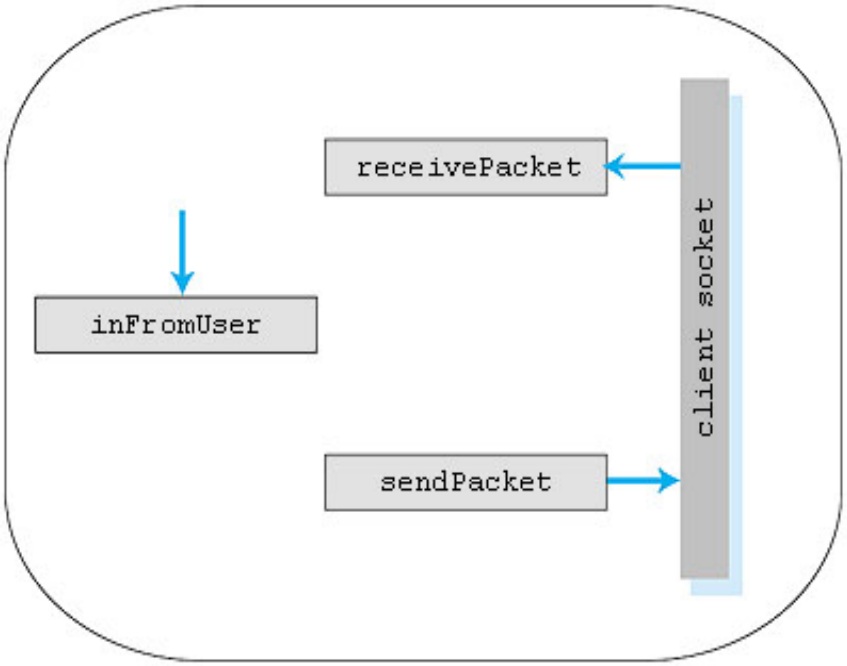
extends Object

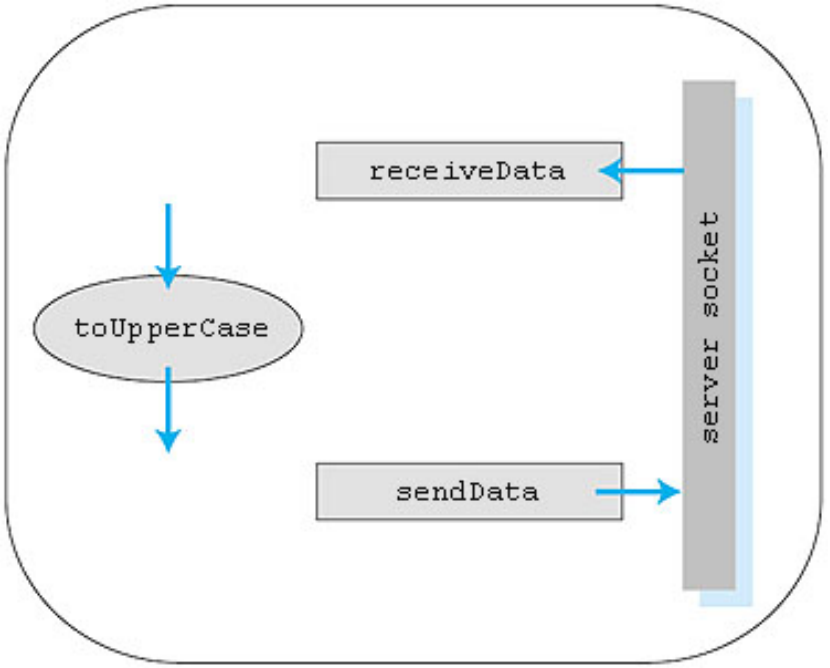
# DatagramSocket Class

- Used for both client and server
- New socket is created using a DatagramSocket() constructor
- 3 constructors



# Example: Java Client and Server (UDP)



# Example: Java Client (UDP)

```
import java.io.*;
import java.net.*;

class UDPClient {
    public static void main(String args[]) throws Exception
    {
```

Create input stream

```
BufferedReader inFromUser =
  new BufferedReader(new InputStreamReader(System.in));
```

Create client socket

```
DatagramSocket clientSocket = new DatagramSocket();
```

Translate hostname to IP address using DNS

```
InetAddress IPAddress = InetAddress.getByName("host");
```

Create input and output buffer

```
byte[] sendData = new byte[1024];
byte[] receiveData = new byte[1024];

String sentence = inFromUser.readLine();

sendData = sentence.getBytes();
```

# Example: Java Client (UDP)

Create datagram with data-to-send, length, IP addr, port

```
DatagramPacket sendPacket =
        new DatagramPacket(sendData, sendData.length,
                                        IPAddress, 9876);
```

Send datagram to server

```
clientSocket.send(sendPacket);
```

```
DatagramPacket receivePacket =
   new DatagramPacket(receiveData, receiveData.length);
```

Read datagram from server

```
clientSocket.receive(receivePacket);
```

```
String modifiedSentence =
    new String(receivePacket.getData());

System.out.println("FROM SERVER:" + modifiedSentence);
clientSocket.close();
}

}
```

# Example: Java Server (UDP)


```
import java.io.*;
import java.net.*;

class UDPServer {
  public static void main(String args[]) throws Exception
    {
```

Create datagram socket at port 9876

```
DatagramSocket serverSocket =
                                new DatagramSocket(9876);

byte[] receiveData = new byte[1024];
byte[] sendData  = new byte[1024];

while(true)
  {
```

Create space for received datagram

```
DatagramPacket receivePacket =
  new DatagramPacket(receiveData, receiveData.length);
```

Receive datagram

```
serverSocket.receive(receivePacket);
```

# Example: Java Server (UDP)

```
String sentence = new String(receivePacket.getData());

InetAddress IPAddress = receivePacket.getAddress();
int port = receivePacket.getPort();

String capitalizedSentence = sentence.toUpperCase();

sendData = capitalizedSentence.getBytes();

DatagramPacket sendPacket =
   new DatagramPacket(sendData, sendData.length,
                                IPAddress, port);

serverSocket.send(sendPacket);
}
}
}
```

Get IP addr port #, of sender

Create datagram to send to client

Write out datagram to socket

End of while loop, loop back and wait for another datagram

# DNS Lookups

- InetAddress contains an IP address as String and as int
- Can also be used for explicit DNS lookups:
  - `InetAddress addr = InetAddress.getByName("www.epfl.ch"); System.out.println(addr.getHostAddress());`
  - `InetAddress addr = InetAddress.getByName("128.178.50.137"); System.out.println(addr.getHostName());`
  - `InetAddress.getAllByName()` to get all IP addresses of a host name
- InetAddress is rarely needed:
  Socket constructors accept IP addresses, names, and objects of type InetAddress (implicit DNS)

# Reading Directly from a URL

- Java provides a number of functions that make programming much easier:

```
import java.net.*;
import java.io.*;

public class URLReader {
    public static void main(String[] args) throws Exception {
        URL yahoo = new URL("http://www.yahoo.com/");
        BufferedReader in = new BufferedReader(
                            new InputStreamReader(
                            yahoo.openStream()));
        String inputLine;
        while ((inputLine = in.readLine()) != null)
            System.out.println(inputLine);
        in.close();
    }
}
```

Open URL as stream

Read and display the web page

No need to implement HTTP

# Writing to a URLConnection

- Possible to read and write to a URL (using HTTP)

```
import java.io.*;
import java.net.*;

public class URLWrite {
    public static void main(String[] args) throws Exception {
        URL url = new URL(
                "http://www.merriam-webster.com/cgi-bin/dictionary");
        URLConnection connection = url.openConnection();
        connection.setDoOutput(true);

        PrintWriter out = new PrintWriter(
                connection.getOutputStream());
        out.println("book=Dictionary&va=java&x=0&y=0");
        out.close();
```

allow writing to the URL

This results in a POST request, rather than GET

# Writing to a URLConnection (2)

get dictionary entry on "java"

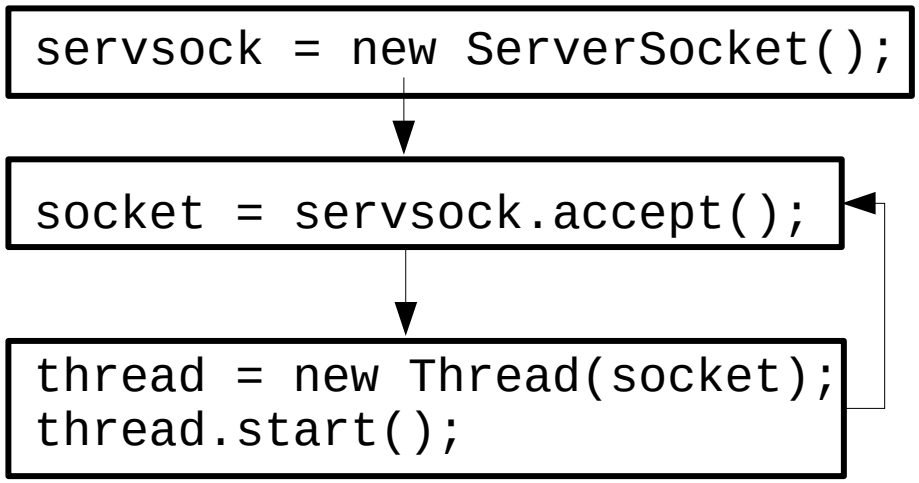
```
            BufferedReader in = new BufferedReader(
                                new InputStreamReader(
                                connection.getInputStream()));
            String inputLine;
            while ((inputLine = in.readLine()) != null)
                System.out.println(inputLine);

            in.close();
        }
    }
```

# Multi-Threaded TCP Server

To be able to handle a larger number of clients the server should not process clients in sequence but in parallel.

- Server continuously listens on server socket for client requests
- When accept( ) returns a socket, start a new thread to handle the client; hand over the socket to the thread
- Separate threads are usually only used for TCP, not for UDP




Java Threads

- "light-weight" process
- shares memory, etc. with parent (possible conflicts!)
- Extend class Thread and overwrite `run( )` (the "`main`" function of a thread)

# Example: Multi-Threaded TCP Server

```
import java.net.*;
import java.io.*;

public class TCPMultiServer {
    public static void main(String[] args) throws Exception {

        serverSocket = new ServerSocket(4444);

        while (true) {
            TCPMultiServerThread thread = new
                TCPMultiServerThread(serverSocket.accept());
            thread.start();
        }
        serverSocket.close();
    }
}
```

Create thread for new socket

# Example: Server Thread

```
import java.io.*;
import java.net.*;

public class TCPMultiServerThread extends Thread {
    private Socket socket = null;

    public TCPMultiServerThread(Socket socket) {
            super("TCPMultiServerThread");
            this.socket = socket;
    }

    public void run() {
      String clientSentence;
      String capitalizedSentence;

      BufferedReader inFromClient =
            new BufferedReader(new InputStreamReader(
                  socket.getInputStream()));
```

Socket handed over from main server

Create input stream, attached to socket

# Example: Server Thread (2)

Create output stream, attached to socket

```
DataOutputStream  outToClient =
  new DataOutputStream(
            connectionSocket.getOutputStream());
```

Read in line from socket

```
clientSentence = inFromClient.readLine();
```

aaaa

```
capitalizedSentence = clientSentence.toUpperCase() + '\n';
```

Write out line to socket

```
outToClient.writeBytes(capitalizedSentence);
```

AAAA

```
close(socket);
    }
}
```

# Exception Handling

- Distributed application: many things can go wrong!
  - Client request to server: host not available, overloaded, behind firewall, no server listening on destination port,...
  - Creating a server socket: socket already in use
  - DNS errors
  - Worst of all: transient thread-errors due to timing and synchronization problems
- Easy: writing network code that works if everything ok
- Hard: writing robust network code!
  - One aspect ignored in examples: exception handling
    - Required for almost all network-related operations
    - try {...} catch (IOException ex) {...}
  - Murphy's Law applies...

# Socket Programming in C/C++

- C/C++ still significantly faster than Java (although this only matters if the network isn't the bottleneck)
- Operating system (and therefore the OS side of sockets) traditionally programmed in C/C++
- C/C++ has a much lower level of abstraction
  - C/C++ provides more functionality
  - Java does many things automatically that you have to do by hand in C/C++
  - Network programming is easy to get wrong: C/C++ makes it even a bit harder

# TCP Socket Programming in C/C++

## Client side

- `socket()` returns client socket ID
- `connect()` with server IP address and port, sends connection request
- `send()` sends data via client socket
- `recv()` receives from socket
- `close()` closes connection

Note: no explicit `connect`, `listen`, and `bind` in Java

## Server side

- `socket()` returns server socket ID
- `bind()` binds socket to server IP address and port
- `listen()` waits for connection request on server socket
- `accept()` accepts connection request and returns id of a new socket for communication with the client
- `send(), recv(), close()` same as for the client socket

# UDP Socket Programming in C/C++

## Client side

- `socket()` returns client socket ID
- `sendto()` sends data via client socket; need to specify IP addr. and port
- `recvfrom()` receives from socket
- `bind()` is optional
- `close()` closes socket

Note: OS supplies local IP address and port if `bind()` is not used

## Server side

- `socket()` returns server socket ID
- `bind()` binds socket to server IP address and port
- `sendto()` sends data via client socket; need to specify IP addr. and port
- `recvfrom()` receives from socket
- `close()` closes socket

# Raw Sockets

- Raw sockets allow to create raw IP packets (bypassing the transport layer)
  - use type `SOCK_RAW` when calling `socket()`
  - no port numbers!
  - access similar to datagram sockets
- Necessary e.g. to implement ping (ICMP)
- Only the superuser (root) may create raw sockets

Note: Raw sockets are not supported in Java

# Example: TCP Server in C

```
#include "inet.h"

int main(int argc, char *argv[]) {
    int sd, newSd, rc, i, n, cliLen;

    struct sockaddr_in cliAddr, servAddr;                    // addresses
    char msg[MAX_MSG];

    sd = socket(AF_INET,SOCK_STREAM,0);     // create socket

    // bind socket
    servAddr.sin_family = AF_INET;
    servAddr.sin_addr.s_addr = htonl(INADDR_ANY);
    servAddr.sin_port = htons(SERVER_PORT);
    rc = bind(sd, (struct sockaddr *) &servAddr, sizeof(servAddr));

    listen(sd, 5);
```

# Example: TCP Server in C

```
   // server infinite loop

   while(1) {
      cliLen = sizeof(cliAddr);
      newSd = accept(sd, (struct sockaddr *) &cliAddr, &cliLen);

      n = recv(newSd, msg, MAX_MSG, 0);

      msg = str_to_upper(msg);       // not implemented here

      write(newSd, msg, n);

      close(newSd);
   } // end of infinite loop
}
```

# Summary : Socket Programming

- TCP

Server process must first be running and created server socket

Client creates client-local TCP socket specifying IP address, port number of server socket

Client TCP connects to server TCP

Server creates new TCP socket for server process to communicate with client (possibly in new Thread)

TCP provides reliable, in-order transfer of bytes between client and server

Client and Server processes uses streams for input and output data

- UDP

Server process must first be running and have created a socket

Client creates client-local socket and group data in packets specifying each IP address, port number of server process at server socket

UDP provides unreliable transfer of datagrams between client and server

Client and Server processes use datagrams for input and output data

# Summary

- Java socket programming
  - higher level of abstraction than C/C++
  - introduction to most important functions
  - more sophisticated functions: access to socket options, multicast communication, etc.
- Different communication models
  - TCP streams - byte data pipes
  - server socket for accepting incoming connections
  - UDP datagrams - isolated messages
  - Raw IP sockets (not in Java)
- References:
  - Pointers under “resources” on class web site
  - Elliotte R. Harold, Java Network Programming (3rd ed), O'Reilly, 2004.