Distributed Systems

01r. Sockets Programming Introduction

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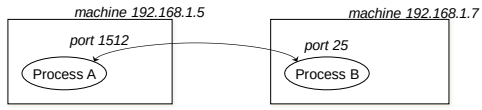
Machine vs. transport endpoints

- IP is a network layer protocol: packets address only the machine
  - IP header identifies source IP address, destination IP address
- IP packet delivery is not guaranteed to be reliable or in-order
- Transport-level protocols on top of IP: TCP & UDP
  - Allow application-to-application communication
  - *Port numbers:* identify communication "channel" at each host



TCP/IP

- Connection-oriented service
- Packets are acknowledged (sender will retransmit missing data)
- Checksum to validate data
- Data may be transmitted simultaneously in both directions
- No record markers – data arrives as a stream of bytes (in the correct order)
- TCP also does
  - Flow control: doesn't send more data than the other side can accept
  - Congestion control: slows down rate of transmission if the network appears to be congested (too many lost packets)

20 bytes

Src port	Dest port
Sequence number	
Acknowledgement number	
Header length / flags	window
checksum	Urgent ptr
Options and pad	

TCP header

UDP/IP

- Datagram service
- Packet may be lost
- Data may arrive out of sequence
- Checksum for data but no retransmit
  - Receiver drops packets with damaged data
- Message-based communication
  - If you send 3 messages of *i, j, k* bytes the receiver will receive 3 messages of *i, j, k* bytes
  - With TCP, you may receive one message of *i+j+k* bytes

8 bytes

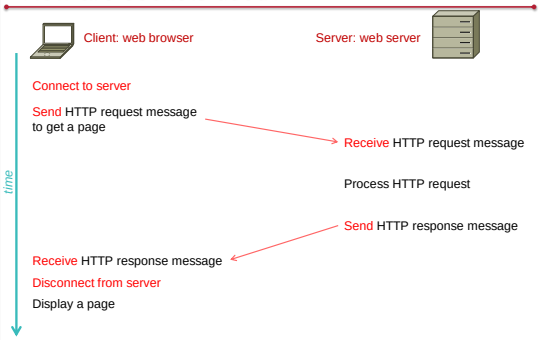
Src port	Dest port
Header length	checksum

UDP header

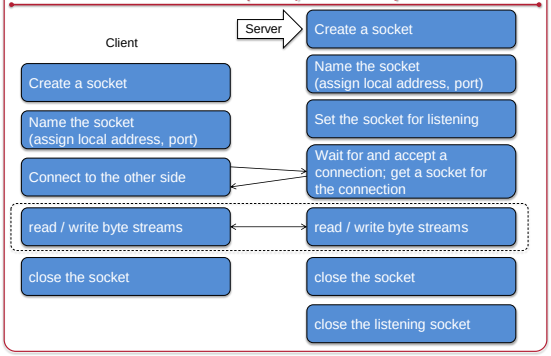
What is a **socket**?

Abstract object from which messages are sent and received
- Looks like a file descriptor to programs
- Application can select particular style of communication
  - Stream (connection-oriented) or datagram (connectionless)
- Unrelated processes need to locate communication endpoints
  - Sockets have a name
  - Name is meaningful in the communications domain
    - For IP networking, name = { address & port number }

How are sockets used?



Connection-Oriented (TCP) socket operations



POSIX system call interface

	System call	Function
server	socket	Create a socket
	bind	Associate an address with a socket
	listen	Set the socket to listen for connections
	accept	Wait for incoming connections
client	connect	Connect to a socket on the server
	read/write, sendto/recvfrom, sendmsg/recvmsg	Exchange data
	close/shutdown	Close the connection

Using sockets in Java

java.net package

- **Socket** class
  - Deals with sockets used for TCP/IP communication
- **ServerSocket** class
  - Deals with sockets used for accepting connections
- **DatagramSocket** class
  - Deals with datagram packets (UDP/IP)

Both Socket and ServerSocket rely on the SocketImpl class to actually implement sockets

- But you don't have to think about that as a programmer

Create a socket for listening: server

Server:

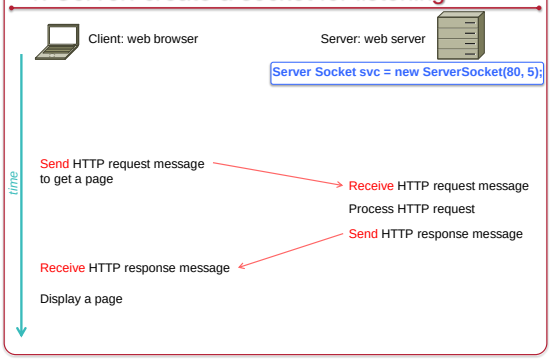
- *create*, *name*, and *listen* are combined into one method
- **ServerSocket** constructor

port *backlog*

```
ServerSocket svc = new ServerSocket(80, 5);
```

Several other flavors (see API reference)

1. Server: create a socket for listening

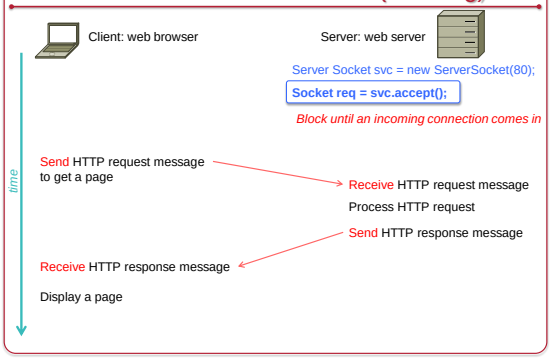


Server: wait for (accept) a connection

- **accept** method of **ServerSocket**
  - block until connection arrives
  - return a **Socket**

```
ServerSocket svc = new ServerSocket(80, 5);
Socket req = svc.accept();
```

2. Server: wait for a connection (blocking)



Client: create a socket

Client:

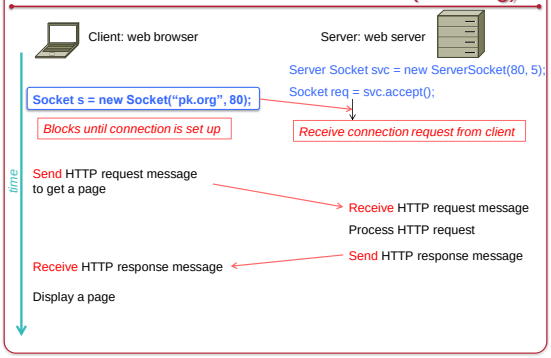
- *create*, *name*, and *connect* operations are combined into one method
- **Socket** constructor

```
Socket s = new Socket("www.rutgers.edu", 2211);
```

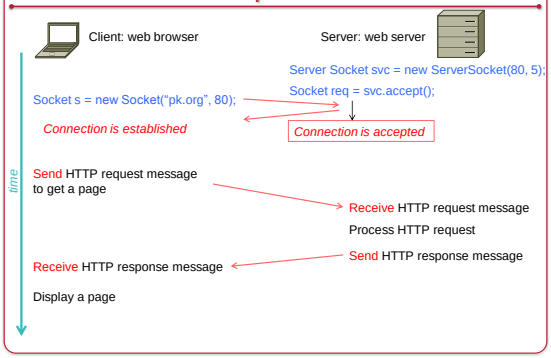
(*host*, *port*)

Several other flavors (see api reference)

3. Client: connect to server socket (blocking)



3a. Connection accepted



Exchange data

- Obtain InputStream and OutputStream from Socket
  - layer whatever you need on top of them
    - e.g. DataInputStream, PrintStream, BufferedReader, …

Example:

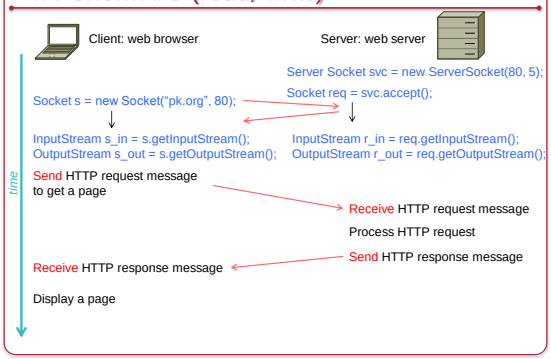
client

```
DataInputStream in = new DataInputStream(s.getInputStream());
PrintStream out = new PrintStream(s.getOutputStream());
```

server

```
DataInputStream in = new BufferedReader(
      new InputStreamReader(req.getInputStream()));
String line = in.readLine();
DataOutputStream out = new DataOutputStream(
            req.getOutputStream());
out.writeBytes(mystring + '\n')
```


4. Perform I/O (read, write)



Close the sockets

Close input and output streams first, then the socket

client:

```
try {
    out.close();
    in.close();
    s.close();
} catch (IOException e) {}
```

server:

```
try {
    out.close();
    in.close();
    req.close();    // close connection socket
    svc.close();    // close ServerSocket
} catch (IOException e) {}
```


Programming with sockets: Sample program

Sample Client-Server Program

To illustrate programming with TCP/IP sockets, we'll write a small client-server program:

– Client:
1. Read a line of text from the user
2. Send it to the server; wait for a response (single line)
3. Print the response

– Server
1. Wait for a connection from a client
2. Read a line of text
3. Return a response that contains the length of the string and the string converted to uppercase
4. Exit

Sample Client-Server Program

We will then embellish this program to:
– Have a continuously-running server
– Allow a client to send multiple lines of text
– Make the server multi-threaded so it can handle concurrent requests
– Specify a host on the command line

Classes for input/output

With Java, you'll often layer different input/output stream classes depending on what you want to do.

Here are some common ones:

Input
- InputStream
- BufferedReader
- InputStreamReader

Output
- OutputStream
- DataOutputStream
- PrintStream
- DataOutputStream

Handling output

OutputStream	The basics – write a byte or a bunch of bytes
DataOutputStream	Allows you to write Unicode (multibyte) characters, booleans, doubles, floats, ints, etc. *Watch out if using this because the other side might not be Java and might represent the data differently.* The two most useful things here are *writeBytes*(String s), which writes a string out as a bunch of 1-byte values and *write*(byte[] b, int off, int len), which writes a sequence of bytes from a byte array.
PrintStream	Allows you to use *print* and *println* to send characters. Useful for line-oriented output.
FilterOutputStream	Needed for *PrintStream*. On it's own, just gives you the same write capabilities you get with *OutputStream*

Handling input

InputStream	The basics – read a byte or a bunch of bytes
BufferedReader	Buffers input and parses lines. Allows you to read data a line at a time via *readLine*(). You can also use *read*(char [] cbuf, int off, int len) to read characters into a portion of an array.
InputStreamReader	You need this to use BufferedReader. It converts bytes (that you'll be sending over the network) to Java characters.

Client: step 1

Read a line of text from the standard input (usually keyboard)

– We use *readLine* to read the text. For that, we need to use the BufferedReader class on top of the *InputStreamReader* on top of the system input stream (*System.in*)

```
String line;
BufferedReader userdata = new BufferedReader(new InputStreamReader(System.in));
line = userdata.readLine();
```


Test #1

Don't hesitate to write tiny programs if you're not 100% sure how something works!

```
import java.io.*;

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

                BufferedReader userdata = new BufferedReader(new InputStreamReader(System.in));
                line = userdata.readLine();
                System.out.println("got: \"" + line + "\");
        }
}
```

Notice that readLine() removes the terminating newline character from a line

– If we want to send line-oriented text, we'll need to suffix a newline ('\n') to the string

Client: step 2

- Establish a socket to the server, send the line, and get the result
  - Create a socket.
  - For now, we will connect to ourselves – the name "localhost" resolves to our local address.
  - For now, we will hard-code a port number: 12345

```
Socket sock = new Socket("localhost", 12345);    // create a socket and connect
```

- Get input and output streams from the socket
  - The methods getInputStream() and getOutputStream() return the basic streams for the socket
  - Create a DataOutputStream for the socket so we can write a string as bytes
  - Create a BufferedReader so we can read a line of results from the server

```
DataOutputStream toServer = new DataOutputStream(sock.getOutputStream());
BufferedReader fromServer = new BufferedReader(
                                new InputStreamReader(sock.getInputStream()));
```


Client: step 3

- Send the line we read from the user and read the results

```
toServer.writeBytes(line + '\n');       // send the line we read from the user

String result = fromServer.readLine();     // read the response from the server
```

- We're done; print the result and close the socket

```
System.out.println(result);

sock.close();
```


Our client – version 1

But we can't test it yet because we don't have the server!

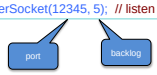
```
import java.io.*;
import java.net.*;

public class TCPClient {
        public static void main(String args []) throws Exception {
                String line;            // user input
                BufferedReader userdata = new BufferedReader(new InputStreamReader(System.in));

                Socket sock = new Socket("localhost", 12345);          // connect to localhost port 12345
                DataOutputStream toServer = new DataOutputStream(sock.getOutputStream());
                BufferedReader fromServer = new BufferedReader(
                                                new InputStreamReader(sock.getInputStream()));

                line = userdata.readLine();                     // read a line from the user
                toServer.writeBytes(line + '\n');               // send the line to the server
                String result = fromServer.readLine();          // read a one-line result
                System.out.println(result);                     // print it
                sock.close();                                   // and we're done
        }
}
```

Server: step 1

Create a socket for listening

- This socket's purpose is *only* to accept connections
- Java calls this a ServerSocket
- For now, we'll use a hard-coded port: 12345
  - If the port number is 0, the operating system will assign a port.
- The backlog is the maximum queue length for unserviced arriving connections
  - The backlog is missing or 0, a default backlog will be used

```
ServerSocket svc = new ServerSocket(12345, 5);  // listen on port 12345
```



Server: step 2

Wait for a connection

- This method will block until a connection comes in
- When a client connects to port 12345 on this machine, the accept() method will return a new socket that is dedicated to communicating to that specific client

```
Socket conn = svc.accept();     // get a connection
```


Test #2

- We can now test that a client can connect to the server
- Let's write a tiny server that just waits for a connection and then exits

```
import java.net.*;

public class wait {
        public static void main(String args[]) throws Exception {
                ServerSocket svc = new ServerSocket(12345, 5);  // listen on port 12345

                Socket conn = svc.accept();     // get a connection
        }
}
```

- Now run the client in another window
  - As soon as the client starts, it will establish a connection and the server will exit

Server: step 3

Get input/output streams for the socket

- We will create a *BufferedReader* for the input stream so we can use readLine to read data a line at a time
- We will create a *DataOutputStream* for the output stream so we can write bytes.

```
// get the input/output streams for the socket
BufferedReader fromClient = new BufferedReader(
                                new InputStreamReader(conn.getInputStream()));
DataOutputStream toClient = new DataOutputStream(conn.getOutputStream());
```


Server: step 4

- Read a line of data from the client (via *fromClient*)

```
String line = fromClient.readLine();                // read the data
System.out.println("got line \"" + line + "\"");    // debugging! Let's see what we got
```

- Create the result

```
// do the work
String result = line.length() + ": " + line.toUpperCase() + '\n';
```

- Write the result to the client (via *writeBytes*)

```
toClient.writeBytes(result);    // send the result
```


Server: step 5

Done! Close the socket

- Close the socket to the client to stop all communication with that client
- Close the listening socket to disallow any more incoming connections. Servers often run forever and therefore we often will not do this.

```
System.out.println("server exiting\n");     // debugging message
conn.close();           // close connection
svc.close();            // stop listening
```

Our server – version 1

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

public class TCPServer {
        public static void main(String args[]) throws Exception {
                ServerSocket svc = new ServerSocket(12345, 5); // listen on port 12345

                Socket conn = svc.accept();     // wait for a connection

                // get the input/output streams for the socket
                BufferedReader fromClient = new BufferedReader(
                                                        new InputStreamReader(conn.getInputStream()));
                DataOutputStream toClient = new DataOutputStream(conn.getOutputStream());

                String line = fromClient.readLine();                // read the data from the client
                System.out.println("got line \"" + line + "\"");    // show what we got

                String result = line.length() + ": " + line.toUpperCase() + '\n';       // do the work

                toClient.writeBytes(result);    // send the result

                System.out.println("server exiting\n");
                conn.close();                   // close connection
                svc.close();                    // stop listening
        }
}
```


Test #3

- Compile TCPServer.java and TCPClient.java
  - javac *.java
- In one window, run
  - java TCPServer
- In another window, run
  - java TCPClient
- The client will wait for input. Type something
  - Hello
- It will respond with the server's output:
  - 5: HELLO

Version 2

- We don't want the server to exit
  - Instead, have it wait for another connection
- Simple:
  - Create the ServerSocket
  - Then put everything else in a forever loop (for(;;))
  - Never close the ServerSocket
- Now we can keep the server running and try running the client multiple times

Our server – version 2

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

public class TCPServer {
        public static void main(String args[]) throws Exception {
                ServerSocket svc = new ServerSocket(12345, 5);  // listen on port 12345

                for (;;) {
                        Socket conn = svc.accept();     // get a connection from a client

                        BufferedReader fromClient = new BufferedReader(
                                                        new InputStreamReader(conn.getInputStream()));
                        DataOutputStream toClient = new DataOutputStream(conn.getOutputStream());

                        String line = fromClient.readLine();    // read the data from the client
                        System.out.println("got line \"" + line + "\"");

                        String result = line.length() + ": " + line.toUpperCase() + '\n';       // do the work

                        toClient.writeBytes(result);    // send the result

                        System.out.println("closing the connection\n");
                        conn.close();           // close connection
                }
        }
}
```


Version 3: let's support multiple lines

Instead of having the server close the connection when a single line of text is received, allow the client to read multiple lines of text

– Each line is sent to the server; the response is read & printed

– An end of file from the user signals the end of user input
  - This is typically control-D on Mac/Linux/Unix systems (see the stty command)

Client – Version 3

- We create a while loop to read lines of text
- When readLine() returns null, that means there's no more.

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

public class TCPClient {
        public static void main(String argv[]) throws Exception {
                String line;  // user input
                BufferedReader userdata = new BufferedReader(new InputStreamReader(System.in));

                Socket sock = new Socket("localhost", 12345);       // connect to localhost port 12345
                DataOutputStream toServer = new DataOutputStream(sock.getOutputStream());
                BufferedReader fromServer = new BufferedReader(
                                                        new InputStreamReader(sock.getInputStream()));

                while ((line = userdata.readLine()) != null) {  // read a line at a time
                        toServer.writeBytes(line + '\n');       // send the line to the server
                        String result = fromServer.readLine();  // read a one-line result
                        System.out.println(result);             // print it
                }
                sock.close();       // we're done with the connection
        }
}
```

Version 3 – server changes

We need to change the server too

- Read lines from a socket until there are no more
- When the client closes a socket and the server tries to read, it will get an end-of-file: readline() will return a null
- A simple loop lets us iterate over the lines coming in from one client

```
while ((line = fromClient.readLine()) != null) {  // while there's data from the client

        // do work on the data

}
System.out.println("closing the connection\n");
conn.close();           // close connection
```


The server handles only one connection

1. Run the server in one window
2. Run the client in another window
   - Type a bunch of text
   - Each line produces a response from the server
3. Run the client again in yet another window
   - Type a bunch of text
   - Nothing happens. There's no connection to the server!
   - You have to exit the first client before this one can connect.
4. We need to make the server multi-threaded

Version 4 – add multi-threading to the server

We define the server to implement Runnable

- Define a constructor: called for each new thread

```
public class TCPServer implements Runnable {
    Socket conn;        // this is a per-thread copy of the client socket
                        // if we defined this static, then it would be shared among threads

    TCPServer(Socket sock) {
        this.conn = sock;           // store the socket for the connection
    }
}
```


Version 4 – add multi-threading to the server

The main function just gets connections and creates threads

```
public static void main(String args[]) throws Exception {
    ServerSocket svc = new ServerSocket(12345, 5);  // listen on port 12345

    for (;;) {
        Socket conn = svc.accept();     // get a connection from a client
        System.out.println("got a new connection");

        new Thread(new TCPServer(conn)).start();
    }
}
```

This creates the thread's state and calls the constructor

This creates the thread of execution and calls *run()* in the thread. When *run* returns, the thread exits.

Version 4 – add multi-threading to the server

The per-connection work is done in the thread

```
public void run() {
    try {
        BufferedReader fromClient = new BufferedReader(new InputStreamReader(conn.getInputStream()));
        DataOutputStream toClient = new DataOutputStream(conn.getOutputStream());
        String line;

        while ((line = fromClient.readLine()) != null) {        // while there's data from the client
            System.out.println("got line \"" + line + "\"");

            String result = line.length() + ": " + line.toUpperCase() + '\n';      // do the work

            toClient.writeBytes(result);    // send the result
        }

        System.out.println("closing the connection\n");
        conn.close();           // close connection and exit the thread
    } catch (IOException e) {
        System.out.println(e);
    }
}
```


Version 5

Allow the client to specify the server name on the command line

- If it's missing, use "localhost"

```
public class TCPClient {
    public static void main(String args[]) throws Exception {
        String line;  // user input
        String server = "localhost";    // default server
        BufferedReader userdata = new BufferedReader(new InputStreamReader(System.in));

        if (args.length > 1) {
            System.err.println("usage: java TCPClient server_name");
            System.exit(1);
        } else if (args.length == 1) {
            server = args[0];
            System.out.println("server = " + server);
        }

        Socket sock = new Socket(server, 12345);      // connect to localhost port 12345
```

The end