

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

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What is a **socket**?

Abstract object from which messages are sent and received

- Looks like a file descriptor to programs
- Provides a communication channel for applications
- 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 }

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How are sockets used?

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Connection-Oriented (TCP) socket operations

Client	Server
Create a socket	Create a socket
Name the socket (assign local address, port)	Name the socket (assign local address, port)
	Set the socket for listening
Connect to the other side	Wait for and accept a connection; get a socket for the connection
read / write byte streams	read / write byte streams
close the socket	close the socket
	close the listening socket

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Connectionless (UDP) socket operations

Client	Server
Create a socket	Create a socket
Name the socket (assign local address, port)	Name the socket (assign local address, port)
Send a message	Receive a message
Receive a message	Send a message
close the socket	close the socket

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POSIX system call interface

This is what the operating system gives up

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

client server

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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

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Create a socket for listening: server

Server:

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

```
ServerSocket svc = new ServerSocket(port, backlog);
```

Several other flavors (see API reference)

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1. Server: create a socket for listening

Client: web browser Server: web server

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

Send HTTP request message to get a page → Receive HTTP request message
 Receive HTTP request message → Process HTTP request
 Process HTTP request → Send HTTP response message
 Send HTTP response message → Receive HTTP response message
 Receive HTTP response message → Display a page

time

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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();
```

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2. Server: wait for a connection (blocking)

Client: web browser Server: web server

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

Block until an incoming connection comes in

Send HTTP request message to get a page → Receive HTTP request message
 Receive HTTP request message → Process HTTP request
 Process HTTP request → Send HTTP response message
 Send HTTP response message → Receive HTTP response message
 Receive HTTP response message → Display a page

time

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Client: create a socket

Client:

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

```
Socket s = new Socket(host, port);
```

Several other flavors (see api reference)

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3. Client: connect to server socket (blocking)

Client: web browser

Server: web server

```
Socket s = new Socket("pk.org", 80);
```

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

```
Socket req = svc.accept();
```

Blocks until connection is set up

Receive connection request from client

time

Send HTTP request message to get a page

Receive HTTP request message

Process HTTP request

Send HTTP response message

Receive HTTP response message

Display a page

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3a. Connection accepted

Client: web browser

Server: web server

```
Socket s = new Socket("pk.org", 80);
```

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

```
Socket req = svc.accept();
```

Connection is established

Connection is accepted

time

Send HTTP request message to get a page

Receive HTTP request message

Process HTTP request

Send HTTP response message

Receive HTTP response message

Display a page

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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');
```

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4. Perform I/O (read, write)

Client: web browser

Server: web server

```
Socket s = new Socket("pk.org", 80);
```

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

```
Socket req = svc.accept();
```

```
InputStream s_in = s.getInputStream();
```

```
OutputStream s_out = s.getOutputStream();
```

```
InputStream r_in = req.getInputStream();
```

```
OutputStream r_out = req.getOutputStream();
```

time

Send HTTP request message to get a page

Receive HTTP request message

Process HTTP request

Send HTTP response message

Receive HTTP response message

Display a page

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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) {}
```

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Programming with sockets: Sample program

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Sample Client-Server Program

To illustrate programming with TCP/IP sockets, we'll write a tiny 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

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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

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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`

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

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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 <code>readLine()</code> . You can also use <code>read(char[] cbuf, int off, int len)</code> to read characters into a portion of an array.
InputStreamReader	You need this to use <code>BufferedReader</code> . It converts bytes (that you'll be sending over the network) to Java characters.

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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();
```

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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

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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()));
```

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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();
```

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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
    }
}
```

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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
```



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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
```

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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

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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());
```

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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
```

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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
```

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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
    }
}
```

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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`

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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

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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
        }
    }
}
```

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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)

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Client – Version 3

We create a while loop to read lines of text

When `readLine()` returns null, that means there's no more data

```
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
    }
}
```

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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
```

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The server handles only one connection

1. Run the server in one window
 - Type a bunch of text
 - Each line produces a response from the server
2. Run the client in 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.
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

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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
    }
}
```

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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.

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

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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
    }
}
```

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The end

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