

packet's source address is put into the variable `clientAddress`. The variable `clientAddress` contains both the client's IP address and the client's port number. Here, `UDPServer` *will* make use of this address information, as it provides a return address, similar to the return address with ordinary postal mail. With this source address information, the server now knows to where it should direct its reply.

```
modifiedMessage = message.decode().upper()
```

This line is the heart of our simple application. It takes the line sent by the client and, after converting the message to a string, uses the method `upper()` to capitalize it.

```
serverSocket.sendto(modifiedMessage.encode(), clientAddress)
```

This last line attaches the client's address (IP address and port number) to the capitalized message (after converting the string to bytes), and sends the resulting packet into the server's socket. (As mentioned earlier, the server address is also attached to the packet, although this is done automatically rather than explicitly by the code.) The Internet will then deliver the packet to this client address. After the server sends the packet, it remains in the while loop, waiting for another UDP packet to arrive (from any client running on any host).

To test the pair of programs, you run `UDPClient.py` on one host and `UDPServer.py` on another host. Be sure to include the proper hostname or IP address of the server in `UDPClient.py`. Next, you execute `UDPServer.py`, the compiled server program, in the server host. This creates a process in the server that idles until it is contacted by some client. Then you execute `UDPClient.py`, the compiled client program, in the client. This creates a process in the client. Finally, to use the application at the client, you type a sentence followed by a carriage return.

To develop your own UDP client-server application, you can begin by slightly modifying the client or server programs. For example, instead of converting all the letters to uppercase, the server could count the number of times the letter *s* appears and return this number. Or you can modify the client so that after receiving a capitalized sentence, the user can continue to send more sentences to the server.

2.7.2 Socket Programming with TCP

Unlike UDP, TCP is a connection-oriented protocol. This means that before the client and server can start to send data to each other, they first need to handshake and establish a TCP connection. One end of the TCP connection is attached to the client socket and the other end is attached to a server socket. When creating the TCP connection, we associate with it the client socket address (IP address and port number) and the server socket address (IP address and port number). With the TCP connection established, when one side wants to send data to the other side, it just drops the

data into the TCP connection via its socket. This is different from UDP, for which the server must attach a destination address to the packet before dropping it into the socket.

Now let's take a closer look at the interaction of client and server programs in TCP. The client has the job of initiating contact with the server. In order for the server to be able to react to the client's initial contact, the server has to be ready. This implies two things. First, as in the case of UDP, the TCP server must be running as a process before the client attempts to initiate contact. Second, the server program must have a special door—more precisely, a special socket—that welcomes some initial contact from a client process running on an arbitrary host. Using our house/door analogy for a process/socket, we will sometimes refer to the client's initial contact as “knocking on the welcoming door.”

With the server process running, the client process can initiate a TCP connection to the server. This is done in the client program by creating a TCP socket. When the client creates its TCP socket, it specifies the address of the welcoming socket in the server, namely, the IP address of the server host and the port number of the socket. After creating its socket, the client initiates a three-way handshake and establishes a TCP connection with the server. The three-way handshake, which takes place within the transport layer, is completely invisible to the client and server programs.

During the three-way handshake, the client process knocks on the welcoming door of the server process. When the server “hears” the knocking, it creates a new door—more precisely, a *new* socket that is dedicated to that particular client. In our example below, the welcoming door is a TCP socket object that we call `serverSocket`; the newly created socket dedicated to the client making the connection is called `connectionSocket`. Students who are encountering TCP sockets for the first time sometimes confuse the welcoming socket (which is the initial point of contact for all clients wanting to communicate with the server), and each newly created server-side connection socket that is subsequently created for communicating with each client.

From the application's perspective, the client's socket and the server's connection socket are directly connected by a pipe. As shown in Figure 2.28, the client process can send arbitrary bytes into its socket, and TCP guarantees that the server process will receive (through the connection socket) each byte in the order sent. TCP thus provides a reliable service between the client and server processes. Furthermore, just as people can go in and out the same door, the client process not only sends bytes into but also receives bytes from its socket; similarly, the server process not only receives bytes from but also sends bytes into its connection socket.

We use the same simple client-server application to demonstrate socket programming with TCP: The client sends one line of data to the server, the server capitalizes the line and sends it back to the client. Figure 2.29 highlights the main socket-related activity of the client and server that communicate over the TCP transport service.

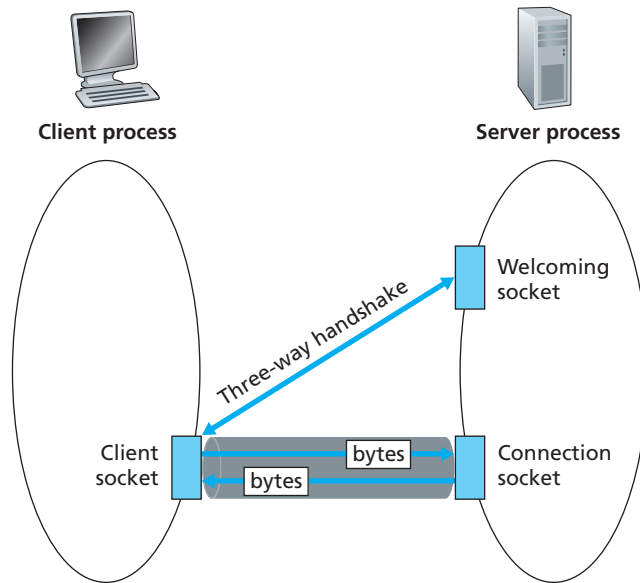


Figure 2.28 ♦ The TCPServer process has two sockets

TCPClient.py

Here is the code for the client side of the application:

```
from socket import *
serverName = 'servername'
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName, serverPort))
sentence = raw_input('Input lowercase sentence:')
clientSocket.send(sentence.encode())
modifiedSentence = clientSocket.recv(1024)
print('From Server: ', modifiedSentence.decode())
clientSocket.close()
```

Let's now take a look at the various lines in the code that differ significantly from the UDP implementation. The first such line is the creation of the client socket.

```
clientSocket = socket(AF_INET, SOCK_STREAM)
```

This line creates the client's socket, called `clientSocket`. The first parameter again indicates that the underlying network is using IPv4. The second parameter

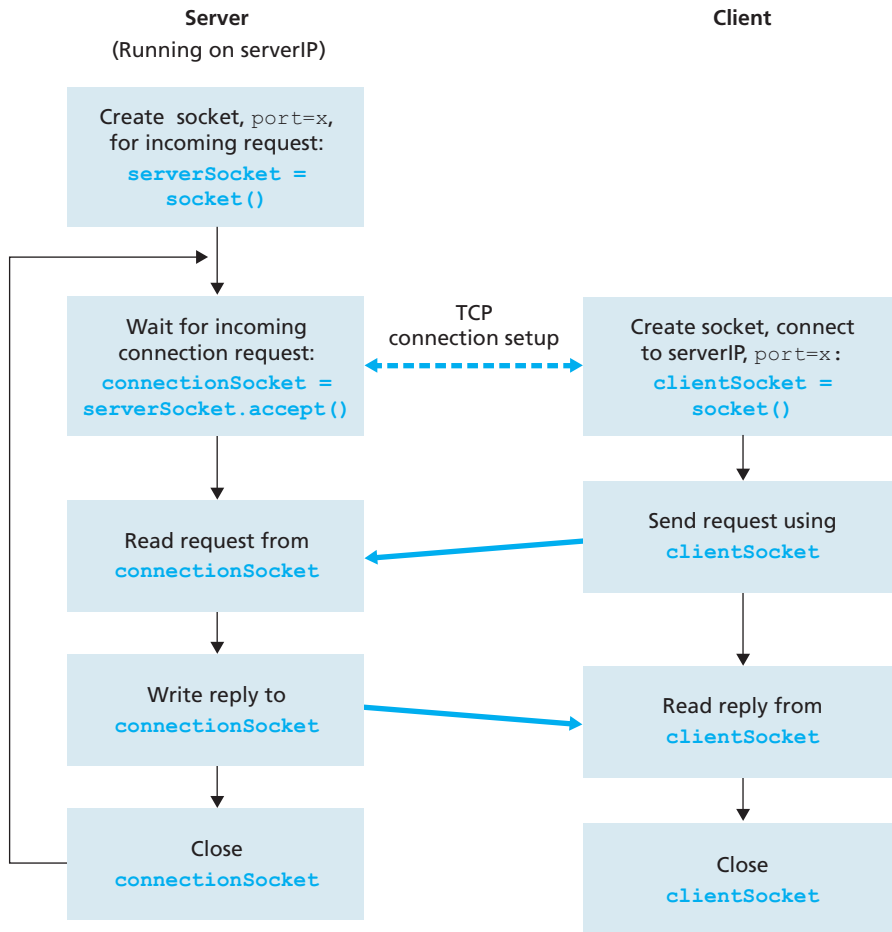


Figure 2.29 ♦ The client-server application using TCP

indicates that the socket is of type `SOCK_STREAM`, which means it is a TCP socket (rather than a UDP socket). Note that we are again not specifying the port number of the client socket when we create it; we are instead letting the operating system do this for us. Now the next line of code is very different from what we saw in `UDPClient`:

```
clientSocket.connect((serverName, serverPort))
```

Recall that before the client can send data to the server (or vice versa) using a TCP socket, a TCP connection must first be established between the client and server. The

above line initiates the TCP connection between the client and server. The parameter of the `connect()` method is the address of the server side of the connection. After this line of code is executed, the three-way handshake is performed and a TCP connection is established between the client and server.

```
sentence = raw_input('Input lowercase sentence:')
```

As with `UDPClient`, the above obtains a sentence from the user. The string `sentence` continues to gather characters until the user ends the line by typing a carriage return. The next line of code is also very different from `UDPClient`:

```
clientSocket.send(sentence.encode())
```

The above line sends the `sentence` through the client's socket and into the TCP connection. Note that the program does *not* explicitly create a packet and attach the destination address to the packet, as was the case with UDP sockets. Instead the client program simply drops the bytes in the string `sentence` into the TCP connection. The client then waits to receive bytes from the server.

```
modifiedSentence = clientSocket.recv(2048)
```

When characters arrive from the server, they get placed into the string `modifiedSentence`. Characters continue to accumulate in `modifiedSentence` until the line ends with a carriage return character. After printing the capitalized sentence, we close the client's socket:

```
clientSocket.close()
```

This last line closes the socket and, hence, closes the TCP connection between the client and the server. It causes TCP in the client to send a TCP message to TCP in the server (see Section 3.5).

TCPServer.py

Now let's take a look at the server program.

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET, SOCK_STREAM)
serverSocket.bind(('', serverPort))
serverSocket.listen(1)
print('The server is ready to receive')
```

```
while True:
    connectionSocket, addr = serverSocket.accept()
    sentence = connectionSocket.recv(1024).decode()
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence.encode())
    connectionSocket.close()
```

Let's now take a look at the lines that differ significantly from UDPServer and TCPClient. As with TCPClient, the server creates a TCP socket with:

```
serverSocket=socket(AF_INET,SOCK_STREAM)
```

Similar to UDPServer, we associate the server port number, `serverPort`, with this socket:

```
serverSocket.bind(('',serverPort))
```

But with TCP, `serverSocket` will be our welcoming socket. After establishing this welcoming door, we will wait and listen for some client to knock on the door:

```
serverSocket.listen(1)
```

This line has the server listen for TCP connection requests from the client. The parameter specifies the maximum number of queued connections (at least 1).

```
connectionSocket, addr = serverSocket.accept()
```

When a client knocks on this door, the program invokes the `accept()` method for `serverSocket`, which creates a new socket in the server, called `connectionSocket`, dedicated to this particular client. The client and server then complete the handshaking, creating a TCP connection between the client's `clientSocket` and the server's `connectionSocket`. With the TCP connection established, the client and server can now send bytes to each other over the connection. With TCP, all bytes sent from one side not only are guaranteed to arrive at the other side but also guaranteed arrive in order.

```
connectionSocket.close()
```

In this program, after sending the modified sentence to the client, we close the connection socket. But since `serverSocket` remains open, another client can now knock on the door and send the server a sentence to modify.

This completes our discussion of socket programming in TCP. You are encouraged to run the two programs in two separate hosts, and also to modify them to achieve slightly different goals. You should compare the UDP program pair with the TCP program pair and see how they differ. You should also do many of the socket programming assignments described at the ends of Chapter 2, 4, and 9. Finally, we hope someday, after mastering these and more advanced socket programs, you will write your own popular network application, become very rich and famous, and remember the authors of this textbook!

2.8 Summary

In this chapter, we've studied the conceptual and the implementation aspects of network applications. We've learned about the ubiquitous client-server architecture adopted by many Internet applications and seen its use in the HTTP, SMTP, POP3, and DNS protocols. We've studied these important application-level protocols, and their corresponding associated applications (the Web, file transfer, e-mail, and DNS) in some detail. We've learned about the P2P architecture and how it is used in many applications. We've also learned about streaming video, and how modern video distribution systems leverage CDNs. We've examined how the socket API can be used to build network applications. We've walked through the use of sockets for connection-oriented (TCP) and connectionless (UDP) end-to-end transport services. The first step in our journey down the layered network architecture is now complete!

At the very beginning of this book, in Section 1.1, we gave a rather vague, bare-bones definition of a protocol: “the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission and/or receipt of a message or other event.” The material in this chapter, and in particular our detailed study of the HTTP, SMTP, POP3, and DNS protocols, has now added considerable substance to this definition. Protocols are a key concept in networking; our study of application protocols has now given us the opportunity to develop a more intuitive feel for what protocols are all about.

In Section 2.1, we described the service models that TCP and UDP offer to applications that invoke them. We took an even closer look at these service models when we developed simple applications that run over TCP and UDP in Section 2.7. However, we have said little about how TCP and UDP provide these service models. For example, we know that TCP provides a reliable data service, but we haven't said yet how it does so. In the next chapter we'll take a careful look at not only the what, but also the how and why of transport protocols.

Equipped with knowledge about Internet application structure and application-level protocols, we're now ready to head further down the protocol stack and examine the transport layer in Chapter 3.