Design and Engineering of Computer Systems

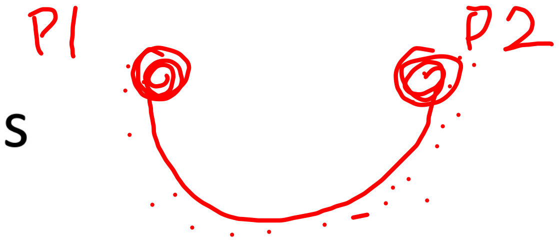
Lecture 18: Network I/O via Sockets

Mythili Vutukuru

IIT Bombay

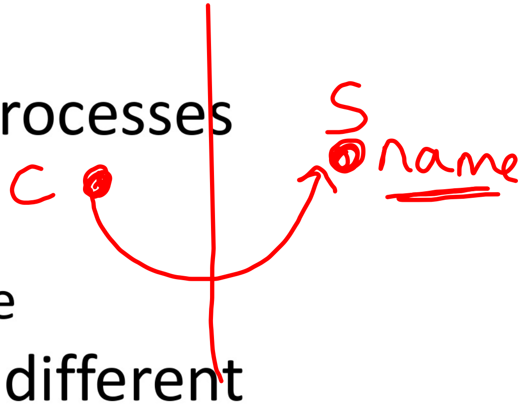
Sockets

- Computers in a computer system exchange messages over the network
  - OS provides system calls to support this communication
- Sockets = abstraction to communicate between two processes
  - Each process opens socket, and pair of sockets can be connected
  - Client-server paradigm: one process opens socket first (server) and another process connects its socket to the first one (client)
  - One process writes a message into one socket, another process can read it, and vice versa (bidirectional communication)
  - Processes can be in same machine or on different machines
- In this lecture: system calls to send/receive messages via sockets
- Next lecture: how socket system calls are implemented

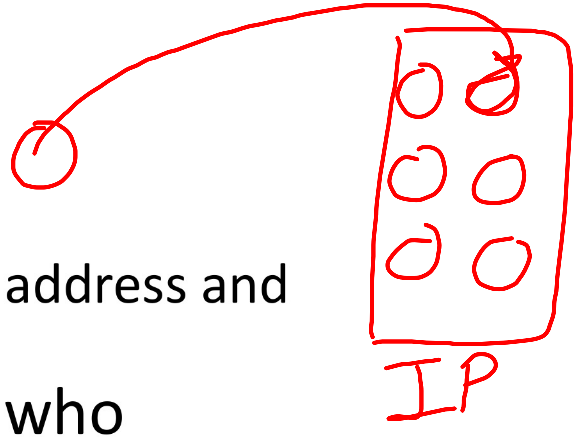


Types of sockets (1)

- Unix domain (local) sockets are used to communicate between processes on the same machine
  - Server process opens socket, and gives it a name (pathname)
  - Client process opens socket, connects to the server socket using its name



- Internet sockets are used to communicate between processes in different machines
  - Every machine on the Internet has an address = IP address
  - Multiple sockets on the machine get unique port numbers (16 bits)
  - Server process opens socket at a well known port number
  - Client process opens socket, connects to the server socket using its IP address and port number



- Client and server sockets differentiated by who starts first and who connects later: server sockets listens for communication on a well-known "address", client process connects to server using the server address
  - Mechanisms exist for clients to learn server addresses

Types of sockets (2)

- Connection-based sockets: one client socket and one server socket are explicitly connected to each other
  - After connection, the two sockets can only send and receive messages to each other
- Connection-less sockets: one socket can send/receive messages to/from multiple other sockets
  - Address of other endpoint can be mentioned on each message
- Type of socket (local or internet, connection-oriented or connection-less) is specified as arguments to system call that creates sockets
- Connection-based Internet sockets are called TCP sockets
  - TCP is a protocol to guarantee in-order reliable delivery of messages across Internet
- Connection-less Internet sockets are called UDP sockets
  - UDP is a protocol to exchange messages on Internet without any reliability
- More on TCP and UDP protocols later in the course

Creating a socket

```
sockfd = socket(…)
bind(sockfd, address)
```

- System call "socket" used to create a socket
  - Takes type of socket as arguments
  - Returns socket file descriptor
- Socket file descriptor is similar to file descriptor returned when file is opened
  - Index of entry in file descriptor array, points to socket-based data structures
  - Used as handle for all future operations on the socket
- A socket can optionally bind to an address (pathname or IP address/port number) using "bind" system call
  - Server sockets must always bind to well known address, so that clients can connect
  - Client sockets need not bind, OS can assign temporary address
- Close system call closes a socket when done

Data exchange using connection-less sockets

- Function sendto is used to send a message from one socket to another connection-less socket in another process
  - Arguments: socket fd, message to send, address of remote socket
- Function recvfrom is used to receive a message from a socket
  - Arguments: socket fd, message buffer into which received message is copied, socket address structure into which address of remote endpoint is filled
- When a process receives a message on connection-less socket, it can find out the address of other endpoint which sent message, and use this address to reply back

Client

```
sockfd = socket(..)
char message[1024]
sendto(sockfd, message, server_sockaddr, ..)
```

Server

```
sockfd = socket(..)
bind(sockfd, server_address)
recvfrom(sockfd, message, client_sockaddr, ..)
```

Connecting sockets

- Connection-oriented sockets must be explicitly connected to each other before exchanging messages
- After server binds socket to well-known address, it uses "listen" system call to make the socket listen for new connections
- Client uses "connect" system call to connect to a server listen socket
  - Connect system call blocks until messages exchanged with server to complete connection procedure (more later)
- Server uses "accept" system call to accept new connection requests
  - Accept system call blocks until new connection is received
  - Returns a new socket file descriptor to communicate exclusively with a connected client
- At server: one listen socket to accept new connections, one connected socket for every connected client to send/recv messages

Client

```
sockfd = socket(..)
connect(sockfd, server_sockaddr, ..)
```

Server

```
sockfd = socket(..)
bind(sockfd, server_address)
listen(sockfd, ..)
newsockfd = accept(sockfd, ..)
```

Data exchange using connected sockets

- After client connects to server, pair of sockets used to exchange data
  - Note that per-client connected socket is used at server, not listen socket
  - System calls send/write used to send message on a connected socket
  - System calls recv/read used to receive message on a connected socket
- Arguments to send/recv: socket fd, message buffer, buffer length, flags
  - Return value is number of bytes read/written or error
  - No need to specify socket address on every message, as connected already
  - Send/recv has extra flags argument, as compared to read/write system calls
  - Flags control where system call blocks and other behavior

Client

```
sockfd = socket(..)
connect(sockfd, server_sockaddr, ..)
n = send(sockfd, req_buf, req_len, ..)
n = recv(sockfd, resp_buf, resp_len, ..)
```

Server

```
sockfd = socket(..)
bind(sockfd, server_address)
listen(sockfd, ..)
newsockfd = accept(sockfd, ..)
n = recv(newsockfd, req_buf, req_len, ..)
n = send(newsockfd, resp_buf, resp_len, ..)
```

Concurrent network I/O

```
sockfd = socket(..)
bind(sockfd, server_address)
listen(sockfd, ..)
newsockfd = accept(sockfd, ..)
n = recv(newsockfd, req_buf, req_len)
n = send(newsockfd, resp_buf, resp_len)
```

- What if server is connected to multiple clients?
  - Multiple sockets to manage: listen socket, per-client connected sockets
  - Accept on listen socket, read/recv on connected socket can block until data arrives
  - If server process blocks on one socket, it can neglect other sockets
- How to concurrently handle multiple clients?
  - Server process can create multiple child processes/threads, one per connected client
  - Main server process blocks at accept on listen socket
  - Child processes/threads can block at reading from connected client sockets
  - New client connections as well as existing client communication handled
  - Processes/threads multiplexed on same core, or run in parallel on different cores
- Cannot support very large number of clients due to limit on number of processes or threads a system can support

Event-driven I/O

```
epollfd = epoll_create(..)
epollctl(epollfd, EPOLL_CTL_ADD, sockfd)
while(1)
   ready_fds = epoll_wait(epollfd, ..)
   for each fd in ready_fds
      handle event on fd
      add any new fds to epoll instance
```

- Event-driven or asynchronous I/O API used to concurrently handle I/O from multiple sockets in a single process
  - Example: select, epoll
- Overview of epoll API
  - Process creates an epoll instance, adds file descriptors of interest to be monitored
  - Process blocks on epoll_wait, which returns when there is an event on any of the socket file descriptors (OS takes care of monitoring all fds)
  - When epoll_wait returns, process handles events by performing suitable actions (accept, recv etc.) on the ready file descriptors, and calls epoll_wait when done
  - Single-threaded process enough to handle I/O from multiple concurrent clients
  - Process should not do any blocking action when handling event
- Event-driven APIs available for network I/O, not popular for disk

Network I/O architecture

- Most components in a computer system need to do some network I/O, sometimes as clients and sometimes as servers
  - Web server receives requests from users, contacts database, returns response
- Programming language libraries may provide better APIs for network I/O than the basic socket API discussed here
  - Example: remote procedure call (RPC) APIs invoke server code like function calls
- With any API, design choice to be made between two architectures
  - One thread per connection, blocking/synchronous API
  - Fewer threads, event-driven/asynchronous API
- Event-driven APIs usually have lesser overhead and higher performance, but harder to program, difficult to scale to multiple cores

Summary

- In this lecture:
  - Socket API to communicate between processes
  - Multi-process/multi-thread vs event-driven architecture
- Programming exercise: write code for a client and server that exchange data using sockets. Add functionality for concurrent handling of multiple clients.