CS4254

Computer Network Architecture and Programming

Dr. Ayman A. Abdel-Hamid

Computer Science Department

Virginia Tech

I/O Multiplexing

Outline

- I/O Multiplexing (Chapter 6)
  - Introduction
  - I/O Models
  - Synchronous I/O versus Asynchronous I/O
  - **select** function
  - TCP echo client using **select**
  - **Shutdown** function
  - TCP Echo Server
  - TCP and UDP Echo Server using select (section 8.15)

Introduction 1/2

- TCP echo client is handling two inputs at the same time: standard input and a TCP socket
  - when the client was blocked in a call to read, the server process was killed
  - server TCP sends FIN to the client TCP, but the client never sees FIN since the client is blocked reading from standard input
    - ✓We need the capability to tell the kernel that we want to be notified if one or more I/O conditions are ready.
    - ✓I/O multiplexing (**select**, **poll**, or newer **pselect** functions)

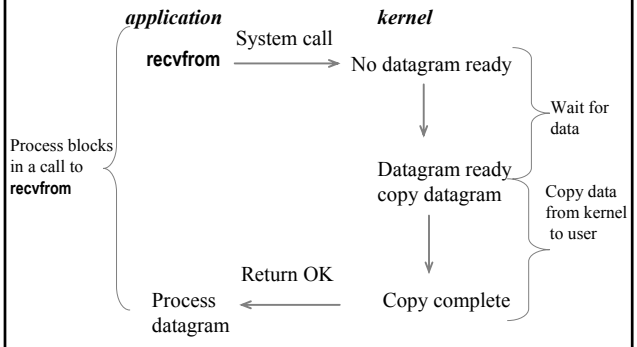
Introduction 2/2

- Scenarios for I/O Multiplexing
  - client is handling multiple descriptors (interactive input and a network socket).
  - Client to handle multiple sockets (rare)
  - TCP server handles both a listening socket and its connected socket.
  - Server handle both TCP and UDP.
  - Server handles multiple services and multiple protocols

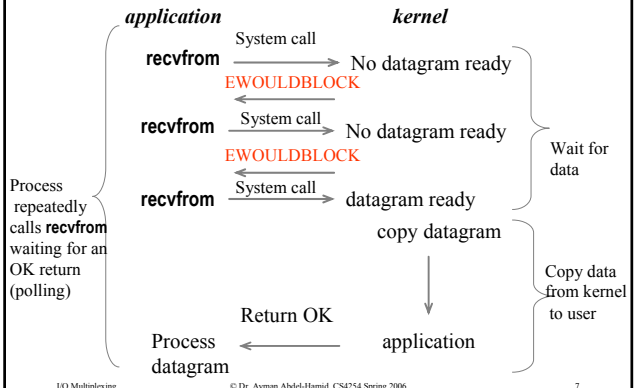
I/O Models

- Models
  - Blocking I/O
  - Nonblocking I/O
  - I/O multiplexing(**select** and **poll**)
  - Signal driven I/O (**SIGIO**)
  - Asynchronous I/O
- Two *distinct phases* for an input operation
  - Waiting for the data to be ready (for a socket, wait for the data to arrive on the network, then copy into a buffer within the kernel)
  - Copying the data from the kernel to the process (from kernel buffer into application buffer)

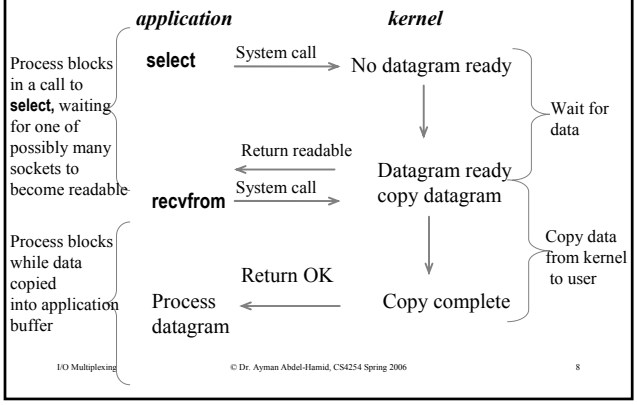
Blocking I/O



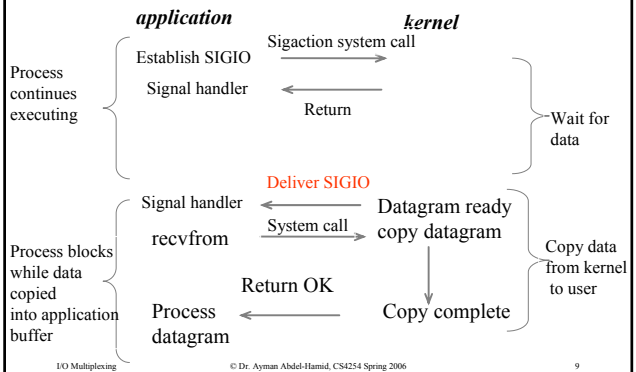
Nonblocking I/O



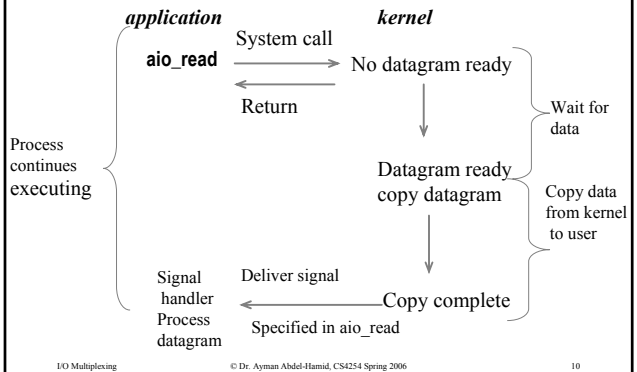
I/O multiplexing(select and poll)



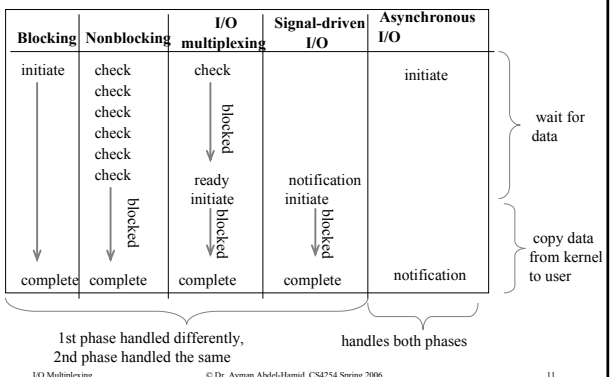
Signal driven I/O (SIGIO)



Asynchronous I/O



Comparison of the I/O Models



Synchronous I/O , Asynchronous I/O

- Synchronous I/O
  - causes the requesting process to be blocked until that I/O operation (recvfrom) completes. (blocking, nonblocking, I/O multiplexing, signal-driven I/O)
- Asynchronous I/O
  - does not cause the requesting process to be blocked

select function

- Allows the process to instruct the kernel to *wait for any one of multiple events to occur* and to wake up the process only when one or more of these events occurs or *when a specified amount of time has passed*.
- What descriptors we are interested in (readable ,writable , or exception condition) and how long to wait?

```
#include <sys/select.h>
   #include <sys/time.h>
   int select (int maxfdp1, fd_set *readset, fd_set *writeset, fd_set
  *exceptset, const struct timeval *);
//Returns: +ve count of ready descriptors, 0 on timeout, -1 on error
struct timeval{
      long  tv_sec;  /* seconds */
      long  tv_usec; /* microseconds */ }
```


Possibilities for select function

- Wait forever : return only when descriptor (s) is ready (specify **timeout** argument as NULL)
- wait up to a fixed amount of time
- Do not wait at all : return immediately after checking the descriptors. Polling (specify **timeout** argument as pointing to a **timeval** structure where the timer value is 0)
- The wait is normally interrupted if the process catches a signal and returns from the signal handler
  - **select** might return an error of **EINTR**
  - Actual return value from function = -1

select function Descriptor Arguments

- **readset** → descriptors for checking readable
- **writeset** → descriptors for checking writable
- **exceptset** → descriptors for checking exception conditions (2 exception conditions)
  - ✓arrival of out of band data for a socket
  - ✓the presence of control status information to be read from the master side of a pseudo terminal (Ignore)
- If you pass the 3 arguments as NULL, you have a high precision timer than the sleep function

Descriptor Sets

- Array of integers : each bit in each integer correspond to a descriptor (**fd_set**)
- 4 macros
  - **void FD_ZERO(fd_set *fdset); /* clear all bits in fdset */**
  - **void FD_SET(int fd, fd_set *fdset); /* turn on the bit for fd in fdset */**
  - **void FD_CLR(int fd, fd_set *fdset); /* turn off the bit for fd in fdset*/**
  - **int FD_ISSET(int fd, fd_set *fdset);/* is the bit for fd on in fdset ? */**

Example of Descriptor sets Macros

```
fd_set  rset;

FD_ZERO(&rset);        /*all bits off : initiate*/
FD_SET(1, &rset);      /*turn on bit fd 1*/
FD_SET(4, &rset);      /*turn on bit fd 4*/
FD_SET(5, &rset);      /*turn on bit fd 5*/
```


maxfdp1 argument to **select** function

- specifies the number of descriptors to be tested.
- Its value is the maximum descriptor to be tested, plus one. (hence maxfdp1)
  - Descriptors 0, 1, 2, up through and including **maxfdp1**-1 are tested
  - example: interested in **fds** 1,2, and 5 → **maxfdp1** = 6
  - Your code has to calculate the **maxfdp1** value
- constant **FD_SETSIZE** defined by including **<sys/select.h>**
  - is the number of descriptors in the **fd_set** datatype. (often = 1024)

Value-Result arguments in select function

- Select modifies descriptor sets pointed to by **readset**, **writeset**, and **exceptset** pointers
- On function call
  - Specify value of descriptors that we are interested in
- On function return
  - Result indicates which descriptors are ready
- Use **FD_ISSET** macro on return to test a specific descriptor in an **fd_set** structure
  - Any descriptor not ready will have its bit cleared
  - You need to turn on all the bits in which you are interested on all the descriptor sets each time you call **select**

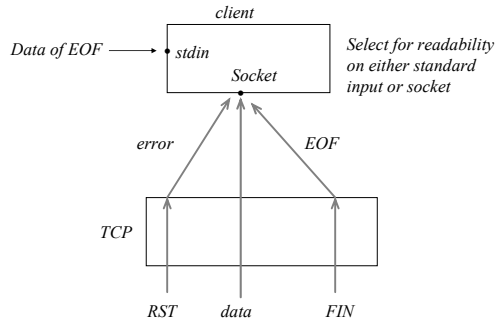
Condition for a socket to be ready for ***select***

Condition	*Readable?*	*writable?*	*Exception?*
Data to read	•		
read-half of the connection closed	•		
new connection ready for listening socket	•		
Space available for writing		•	
write-half of the connection closed		•	
Pending error	•	•	
TCP out-of-band data			•

str_cli Function revisited

- Recall section 5.5 (source code is **lib/str_cli.c**)
- Problems with earlier version
  - ➢ could be blocked in the call to **fgets** when something happened on the socket
  - ➢ We need to be notified as soon s the server process terminates
- Alternatively
  - ➢ block in a call to **select** instead, waiting for either standard input or the socket to be readable.

Condition handled by **select** in **str_cli**



Conditions handled with the socket

- Peer TCP sends data
  - ➢ the socket becomes readable and *read* returns greater than 0 (number of bytes of data)
- Peer TCP sends a FIN (peer process terminates)
  - ➢ the socket become readable and *read* returns 0 (EOF)
- Peer TCP sends a RST (peer host has crashed and rebooted)
  - ➢ the socket become readable and returns -1
  - ➢ *errno* contains the specific error code
- ➢ Source code in **select/strcliselect01.c** tested by **select/tcpcli01.c**
- ➢ This version is OK for stop-an-wait mode (interactive input), will modify later for batch input and buffering

select-based **str_cli** function 1/2

```
void  str_cli(FILE *fp, int sockfd)
{
        int     maxfdp1;
        fd_set  rset;
        char    sendline[MAXLINE], recvline[MAXLINE];

        FD_ZERO(&rset);
        for ( ; ; ) {
                FD_SET(fileno(fp), &rset);
                FD_SET(sockfd, &rset);
                maxfdp1 = max(fileno(fp), sockfd) + 1;
                Select(maxfdp1, &rset, NULL, NULL, NULL);
//Continue…..
```

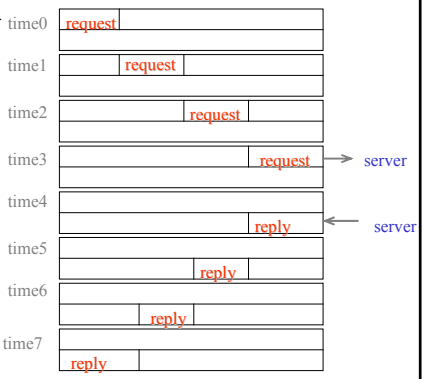
select-based **str_cli** function 2/2

```
        if (FD_ISSET(sockfd, &rset)) {  /* socket is readable */
                if (Readline(sockfd, recvline, MAXLINE) == 0)
                        err_quit("str_cli: server terminated prem");
                Fputs(recvline, stdout);
        }

        if (FD_ISSET(fileno(fp), &rset)) {  /* input is readable */
                if (Fgets(sendline, MAXLINE, fp) == NULL)
                        return;         /* all done */
                Writen(sockfd, sendline, strlen(sendline));
        }
    }//for
}//str_cli
```


Batch Input and Buffering 1/2

client → server

- **str_cli** operates in a stop-and-wait mode → sends a line to the server and then waits for the reply
- Assume RTT of 8 units of time → *only using one-eighth of the pipe capacity*
- Ignore TCP ACKs



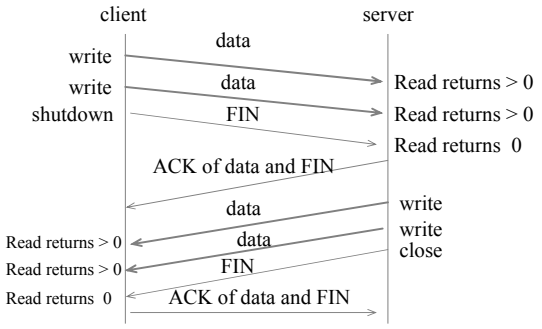
Batch Input and Buffering 2/2

- With batch input, can send as fast as we can
- The problem with the revised **str_cli** function
  - ➢ After the handling of an end-of-file on input, the send function returns to the main function, that is, the program is terminated.
  - ➢ However, in *batch mode*, there are still other requests and replies in the pipe.
- We need a way to close one-half of the TCP connection
  - ➢ send a **FIN** to the server, telling it we have finished sending data, but leave the socket descriptor open for reading
    - ✓**shutdown** function

Shutdown function 1/3

- Close one half of the TCP connection
  - ➢ send **FIN** to server, but leave the socket descriptor open for reading
- Limitations with **close** function
  - ➢ decrements the descriptor's reference count and closes the socket only if the count reaches 0
    - ✓With **shutdown**, can initiate TCP normal connection termination regardless of the reference count
  - ➢ terminates both directions (reading and writing)
    - ✓With **shutdown**, we can tell other end that we are done sending, although that end might have more data to send us

Shutdown function 2/3



Shutdown function 3/3

```
#include<sys/socket.h>
int shutdown ( int sockfd, int howto );
/* return : 0 if OK, -1 on error */
```

- ***howto*** argument
  - **SHUT_RD**
    - ✓ read-half of the connection closed
    - ✓ Any data in receive buffer is discarded
    - ✓ Any data received after this call is ACKed and then discarded
  - **SHUT_WR**
    - ✓ write-half of the connection closed (half-close)
    - ✓ Data in socket send buffer sent, followed by connection termination
  - **SHUT_RDWR**
    - ✓ both closed

str_cli using *select* and *shutdown* 1/2

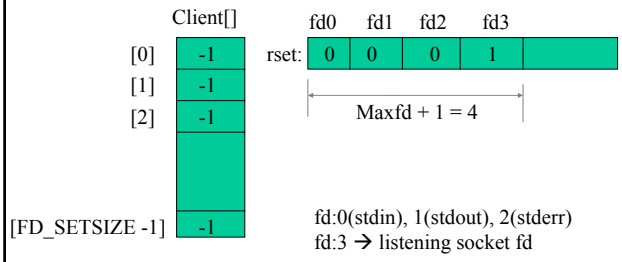
```
//Source code in select/ strcliselect02.c, test with select/tcpcli02.c
#include "unp.h"
void   str_cli(FILE *fp, int sockfd)
{
        int     maxfdp1, stdineof;
        fd_set  rset;
        char    sendline[MAXLINE], recvline[MAXLINE];

        stdineof = 0;
        FD_ZERO(&rset);
        for ( ; ; ) {
                if (stdineof == 0) // select on standard input for readability
                        FD_SET(fileno(fp), &rset);
                FD_SET(sockfd, &rset);
                maxfdp1 = max(fileno(fp), sockfd) + 1;
                Select(maxfdp1, &rset, NULL, NULL, NULL);
//Continue…..
```


str_cli using *select* and *shutdown* 2/2

```
                if (FD_ISSET(sockfd, &rset)) {          /* socket is readable */
                        if (Readline(sockfd, recvline, MAXLINE) == 0) {
                                if (stdineof == 1)
                                        return;         /* normal termination */
                                else
                                        err_quit("str_cli: server terminated prematurely");
                        }
                        Fputs(recvline, stdout);
                }
                if (FD_ISSET(fileno(fp), &rset)) {  /* input is readable */
                        if (Fgets(sendline, MAXLINE, fp) == NULL) {
                                stdineof = 1;
                                Shutdown(sockfd, SHUT_WR);      /* send FIN */
                                FD_CLR(fileno(fp), &rset);
                                continue;
                        }
                        Writen(sockfd, sendline, strlen(sendline));
                }
        }
}
```

TCP echo server using ***select*** 1/5

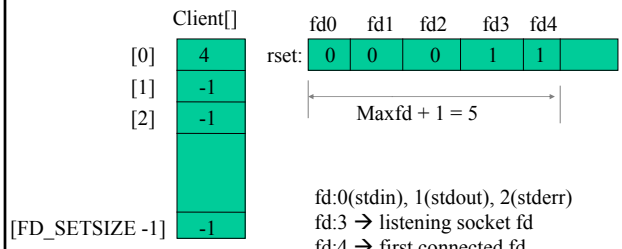
- Rewrite the server as a single process that uses **select** to handle any number of clients, instead of forking one child per client.
- Before first client has established a connection



fd:0(stdin), 1(stdout), 2(stderr)
fd:3 → listening socket fd

TCP echo server using ***select*** 2/5

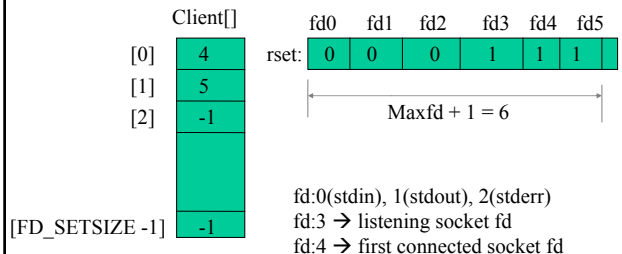
- After first client connection is established (assuming connected descriptor returned by **accept** is 4)



fd:0(stdin), 1(stdout), 2(stderr)
fd:3 → listening socket fd
fd:4 → first connected fd

TCP echo server using ***select*** 3/5

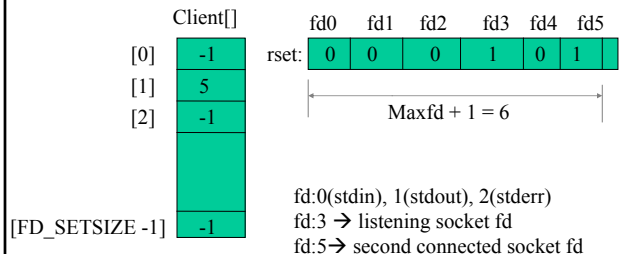
- After second client connection is established (assuming connected descriptor returned by **accept** is 5)



fd:0(stdin), 1(stdout), 2(stderr)
fd:3 → listening socket fd
fd:4 → first connected socket fd
fd:5→ second connected socket fd

TCP echo server using ***select*** 4/5

- First client terminates its connection (**fd** 4 readable and **read** returns 0 → client TCP sent a FIN)



fd:0(stdin), 1(stdout), 2(stderr)
fd:3 → listening socket fd
fd:5→ second connected socket fd

TCP echo server using ***select*** 5/5

- As clients arrive, record connected socket descriptor in first available entry in client array (first entry = -1)
- Add connected socket to read descriptor set
- Keep track of
  - Highest index in client array that is currently in use
  - Maxfd +1
- The limit on number of clients to be served

  Min (FD_SETSIZE, **Max** (Number of descriptors allowed for this process by the kernel))
- Source code in **tcpcliserv/tcpservselect01.c**

TCP and UDP echo server using ***select***

- Section 8.15
- Combine concurrent TCP echo server with iterative UDP server into a single server that uses **select** to multiplex a TCP and UDP socket
- Source code in **udpcliserv/udpservselect01.c**
- Source code for **sig_chld** function (signal handler) is in **udpcliserv/sigchldpidwait.c**
  - Handles termination of a child TCP server
  - See sections 5.8, 5.9, and 5.10