I/O Multiplexing and Non-blocking I/O

COMP 321

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read() and write() Normally Block the Process

Consider, for example, the following typical code

```
while ((nch = read(STDIN_FILENO, buffer, BUFFER_SIZE)) > 0)
    write(STDOUT_FILENO, buffer, nch);
```

- Each read() call "blocks" and doesn't return until it completes
- Each write() call then "blocks" and doesn't return until it completes
- This may be fine in simple cases like the above
- ***But what if you want/need to read/write multiple files "at once" ?***

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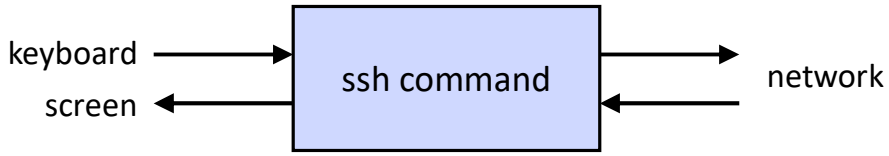
A Simple Example

Consider something like the "ssh" command

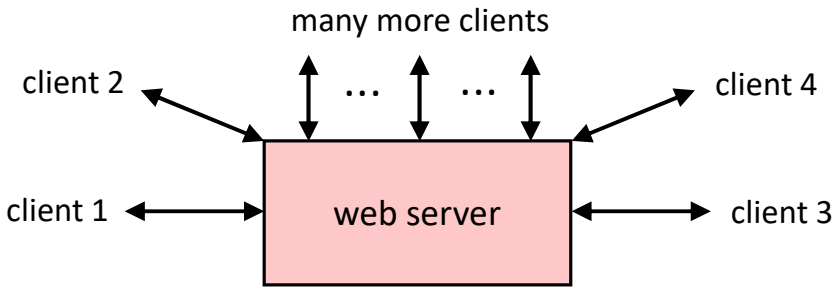
- Read from the keyboard and write to the network connection to the computer you are ssh'd into
- Read from the network connection from the computer you are ssh'd into and write to the screen
- How can the ssh program do all of this (both directions) at once?
- And what about also reading from the mouse and writing to the network?



Another Example

Consider a large, very busy web server

- The web server reads/writes with one web browser client
- While it also reads/writes with another web browser client
- And with another web browser client, etc., for many clients, all at once



A Solution: I/O Multiplexing

The basic idea

- Build a list of all the file descriptors we want to be able to do this kind of I/O on
- Repeat in a loop
  - Give this list of file descriptors to the kernel
  - The kernel blocks this process until at least any one of those descriptors is ready for next I/O operation (e.g., read or write)
    - Example: you typed something on the keyboard
    - Example: the network is ready for the next data you want to send
  - The process performs the read or write for each descriptors indicated ready
  - For each of those reads or writes, the process shouldn't need to be blocked since that descriptor is ready for this next I/O

The select() Kernel Call

```
int  select(int nfds,  fd_set *_Nullable restrict readfds,
            fd_set *_Nullable restrict writefds,
            fd_set *_Nullable restrict exceptfds,
            struct timeval *_Nullable restrict timeout);
```

Allows the calling process to ask to watch multiple file descriptors at once

- The file descriptors to watch are specified by three different fd "sets"
- nfds (awkwardly) specifies the limit on which file descriptors to check
  - nfds = highest file descriptor ***number*** across all 3 sets, ***plus 1***
- timeval can specify a timeout after which to return early, even if no I/O is possible yet for any the indicated file descriptors (across all 3 sets)

The Three File Descriptor Sets

Each defines a set of fds to watch for a different type of I/O

- readfds
  - The set of fds for the kernel to watch if they are ready for reading from
  - Basically, if it is now possible to do a read from it without blocking
- writefds
  - The set of fds for the kernel to watch if they are ready to write to
  - Basically, if it is now possible to do a write to it without blocking
- exceptfds
  - The set of fds for the kernel to watch for "exceptional" conditions
  - Largely unused, so we'll ignore it here

Any of the three can be NULL, meaning that set should be treated as empty set

The Return Values from select()

For each of the readfds, writefds, and exceptfds fd_set inputs

- Modifies each fd_set ***in place*** to remove bits for any fds that are ***not*** ready
- Leaves only the bits set for any fds that ***are*** ready for that type of I/O
- (Overwrites the three original fd_set values!)

And returns the total count of the specified fds that are ready

- That is, the total count of bits still set across the three sets
- Will return 0 if it returns due to a timeval timeout instead of any fds becoming ready

Why Might a read() on an fd Block?

Just a few reasons a read() from an fd might block

- Reading from a regular file never blocks
  - Even at the end of the file
- Reading from a network connection can block if no new data has yet arrived
- Reading from a pipe (or fifo) can block if no data is currently available
  - If all writing fds get closed, then read will not block since end of file
- Reading from a terminal might block
  - If you haven't yet typed ENTER then you might backspace away any input
  - Only characters before most recent ENTER are available to be read
  - A read from terminal may block since available input may be backspaced

Why Might a write() on an fd Block?

Just a few reasons a write() on an fd might block

- Writing to a regular file never blocks
  - Even if the file system (or disk) is full
- Writing to a network connection can block if output buffering is full
  - Must be able to transmit (and with TCP, get acknowledgement) first
- Writing to a pipe (or fifo) can block if the available buffering is full
- Writing to a terminal can block if the available buffering is full
  - A terminal is a slow device, and it might take a while for previous output to complete and free space in output buffering

The Format of an fd_set

Not originally designed very well, but still usable

- A bitmask, with one bit per possible file descriptor number
  - If the bit is set, that fd is "in" the "set"
- Stored as a constant-sized array of integers using typedef "fd_set"
- The number of bits (the size of the bitmask) is defined as FD_SETSIZE
  - Modern Unix/Linux can have almost any number of fds per process
  - But FD_SETSIZE can't be enlarged without recompiling everything, including even the C library
  - Typical size is 1024 bits (that is, array of 32 × 32-bit integers)
- select() only looks at bits up to the "nfds" value passed (i.e., fds 0 … nfds-1)

Manipulating an fd_set

```
fd_set  my_fd_set;
```

- FD_ZERO(&my_fd_set);
  - Changes the set my_fd_set to equal the empty set
- FD_CLR(int fd, &my_fd_set);
  - Removes fd from the set my_fd_set
- FD_SET(int fd, &my_fd_set);
  - Adds fd to the set my_fd_set
- FD_ISSET(int fd, &my_fd_set);
  - Returns true/false if fd is in the set my_fd_set

An Example select() Call

```
fd_set  read_set;
fd_set  write_set;

FD_ZERO(&read_set);
FD_ZERO(&write_set);

FD_SET(0,  &read_set);
FD_SET(7,  &read_set);
FD_SET(1,  &read_set);

FD_SET(4,  &write_set);
FD_SET(2,  &write_set);

status = select(8,  &read_set,  &write_set,  NULL,  NULL);
```


The Use of timeval on select()

Can ask the kernel to return after this limit even if none of the fds are ready

- timeval has fields for seconds (tv_secs) and microseconds (tv_usecs)
- If timeval == NULL
  - select() waits forever, or until at last some specified fds are ready
- If timeval->tv_secs == 0 && timeval->tv_usecs == 0
  - The kernel checks all of the fds for ready, then always returns ***immediately***
- If timeval->tv_secs != 0 || timeval->tv_usecs != 0
  - The kernel returns when any of fds are ready, or after the specified timeout
  - ***Whichever occurs first***
- If ***all*** of readfds, writefds, and exceptfds are NULL, timeval is still used

An Alternative to select(): poll()

```
int  poll(struct pollfd *fds,  nfds_t nfds,  int timeout);
```

A newer, cleaned up interface but roughly still the same

- Input is an array of "struct pollfd"
  - Each specifies fd, events to watch for, and (on return) events that occurred
  - No more bitsmaps or overwriting the input structs as in select()

Comparison between select() and poll()

- select() has existed for a long time and is widely available in Unix-like systems
- poll() is more recent, but it's still been around a long time

A Performance Problem with select() and poll()

These work well enough for a small number of fds, but not for (very) large

- A typical select() or poll() application makes this call over and over again, checking for new status on any of the same fds it is interested in
- But the kernel state to block the process (and know when to unbock the process) for each of those calls must be set up "from scratch" on each call
  - Must add the process to a separate kernel list for each of those fds
- And that kernel state is torn down on the completion of each of those calls
  - Must remove the process from each of those separate lists in the kernel
- No state related to a series of select() or poll() calls can be retained in the kernel (and thus reused) for each of those calls

epoll: More Efficient I/O Multipliexing (Linux Only)

epoll operates through 3 different kernel calls

- epoll_create()
  - Creates a new epoll instance and returns a file descriptor for it
- epoll_ctl()
  - Used to register interest in some fd for a given epoll instance
  - Can add, remove, or modify settings for an fd within that instance
- epoll_wait()
  - Waits for I/O events, blocking the calling process until then
  - The epoll instance state is retained and reused between epoll_wait() calls
  - And changes in fd status are tracked in the instance, ready for the next call

FreeBSD and Solaris have similar (also non-standard) facilities

Non-blocking I/O for a File Descriptor

read() and write() normally block the calling process

- I/O multiplexing can tell you which fds are "ready" for reading or writing
  - Meaning it is now possible to do a read (or write) on it without blocking
- But is that enough to ensure your process never blocks on I/O, even if multiplexing told you the fd is "ready" for that I/O?
- Usually yes, but not always, such as
  - After an indication of ready for a write, a ***large*** write may still block
  - After an indication of ready for a read, if you use, e.g., rio_readlineb(), it may do an ***additional*** read(), if it hasn't reached the newline yet
  - An indication of ready for read only means ready ***then,*** but those available characters might get consumed by ***another*** process before your read
- ***For a solid, robust server, you want to be sure blocking never occurs***

Turning on Non-blocking Mode on an fd

```
int  fcntl(int fd,  int cmd,  ...  /* arg */ );
```

Perform the operation indicated by "cmd" on the file descriptor "fd"

- Two commands are of interest here
  - F_GETFL – gets (returns) the current flags associated with fd
  - F_SETFL – sets the flags for the file descriptor fd to the value arg
- To enable non-blocking mode on file descriptor fd

  fcntl(fd, F_SETFL, fcntl(fd, F_GETFL) | O_NONBLOCK);
- Or, if you happen to want to turn it off for file descriptor fd

  fcntl(fd, F_SETFL, fcntl(fd, F_GETFL) & ~O_NONBLOCK);
- Can also set O_NONBLOCK in the "flags" argument on open()

The Effect of Non-blocking Mode on I/O

Any I/O call on a non-blocking file descriptor will never block

- Any I/O call will still complete normally, if it can
- But if it would instead have to block
  - It will return -1, with errno set to EAGAIN or EWOULDBLOCK
- You can also now use this to handle I/O more efficiently
  - After multiplexing tells you the fd is ready for reading (or writing)
  - You can ***loop*** to read ***all*** available data (or to write ***everything*** you want to)
  - But the loop stops harmlessly on -1 and EWOULDBLOCK, if it needs to
  - Then you wait for multiplexing to tell you again to read (or write)
  - ***Handles I/O with fewer kernel calls, since you might get to handle multiple reads or writes without doing the I/O multiplexing call for each***