CSCB09 Software Tools and Systems Programming

IO Multiplexing // Threads

Marcelo Ponce

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Department of Computer and Mathematical Sciences - UTSC

Today's class

Today we will discuss the following topics:

- IO Multiplexing
- Threads

IO Multiplexing

- One basic concept of Linux systems is the rule that everything in Unix/Linux is a file.
- Each process has a table of file descriptors that point to files, sockets, devices and other operating system objects.
- Not so surprising then is the fact, that processes will have to deal with a large number of files, i.e. FDs.
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There are three main options in Linux: `select`, `poll`, `epoll`

- Typical system that works with many IO sources has an initialization phase and then enter some kind of standby mode – wait for any client to send request and response it
- A tentative "solution" is to create a thread (or process) for each client, block on read until a request is sent and write a response.
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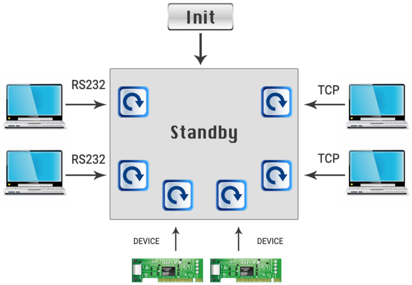
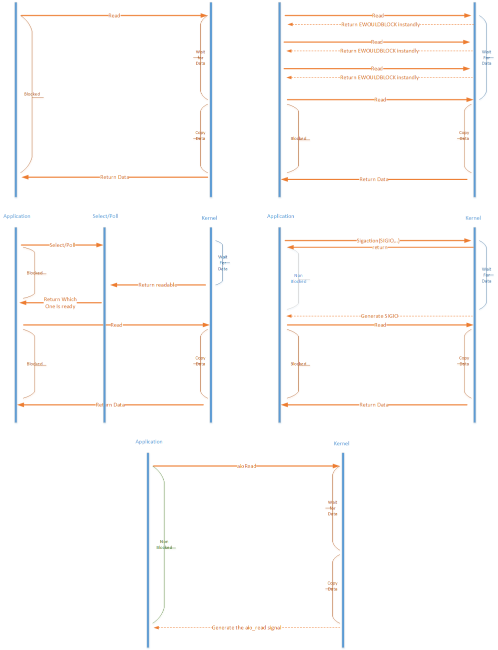
The solution is to use a kernel mechanism for polling over a set of file descriptors.



I/O Models

- Blocking I/O
- Non-blocking I/O
- I/O Multiplexing (`select`/`poll`/...)
- Signal driven I/O (`SIGIO`)
- Asynchronous I/O



`select` system call

The `select()` system call provides a mechanism for implementing synchronous multiplexing I/O

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

A call to `select( )` will **block** until the given FDs are ready to perform I/O, or until an optionally specified timeout has elapsed.

`poll` system call

Unlike `select()`, with its inefficient three bitmask-based sets of file descriptors, `poll()` employs a single array of `nfds` `pollfd` structures

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

```
struct pollfd {
      int fd;
      short events;
      short revents;
};
```

epoll system calls

epoll* system calls help us to create and manage the context in the kernel

- create a context in the kernel using epoll_create
- add and remove file descriptors to/from the context using epoll_ctl
- wait for events in the context using epoll_wait

`select`

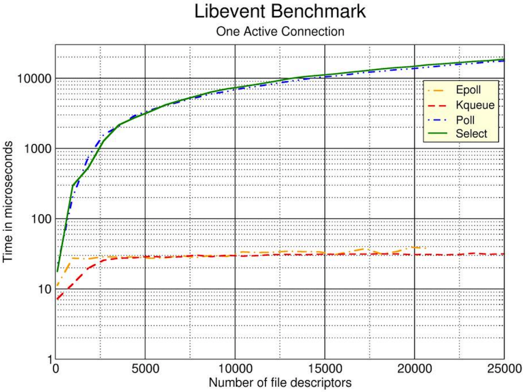
- FD sets statically sized
- FD sets reconstructed on return
- timeout parameter undefined on return
- more portable
- `pselect`

`poll`

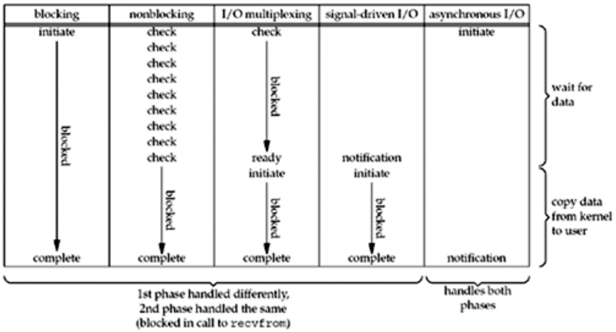
- does not require user to calculate max nbr of FDs
- more efficient for large-valued FDs
- separates input (events) from the output (revents)
- more portable

`epoll`

- can add/remove FDs while waiting
- better performance: $\mathcal{O}(1)$ instead of $\mathcal{O}(n)$
- can behave as level triggered or edge triggered
- linux specific, so non portable



Libevent Benchmark
One Active Connection
Epoll
Kqueue
Poll
Select
Time in microseconds
Number of file descriptors



blocking
nonblocking
I/O multiplexing
signal-driven I/O
asynchronous I/O
initiate
check
blocked
ready
notification
complete
wait for data
copy data from kernel to user
1st phase handled differently, 2nd phase handled the same (blocked in call to recvfrom)
handles both phases

Concurrency

Concurrency

- The two key concepts driving computer systems and applications are
  - communication: the conveying of information from one entity to another
  - concurrency: the sharing of resources in the same time frame
- Concurrency can exist in a single processor as well as in a multiprocessor system
- Managing concurrency is difficult, as execution behaviour is not always reproducible

Concurrency – example

```sh
#!/usr/bin/sh
count=1
while [ $count -le 20 ]
do
  echo -n "a"
  count=`expr $count + 1`
done
```

```sh
#!/usr/bin/sh
count=1
while [ $count -le 20 ]
do
        echo -n "b"
        count=`expr $count + 1`
done
```

- When run sequentially (`a; b`) output is sequential.
- When run concurrently (`a&; b&`) output is interspersed and different from run to run.

Race Conditions

- A Race Condition occurs when multiple processes are trying to do something with shared data and the final outcome depends on the order in which the processes run.
- E.g., If any code after a fork depends on whether the parent or child runs first.
- A parent process can call `wait()` to wait for termination (may block)
- A child process can wait for parent to terminate by polling (wasteful) (How would you do this?)
- One standard solution is to use signals.

Race Condition – Example

Process A		*Process B*
`x = get(count)`		`y = get(count)`
`write(x+1)`	Count	`write(y+1)`
`x=1` ←	$\boxed{1}$	
`write(2)` →	$\boxed{2}$	→ `y=2`
	$\boxed{3}$	← `write(3)`
	✓	

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Threads

- Processes are expensive to create.
- It takes quite a bit of time to switch between processes
- Communication between processes must be done through an external structure - files, pipes, shared memory
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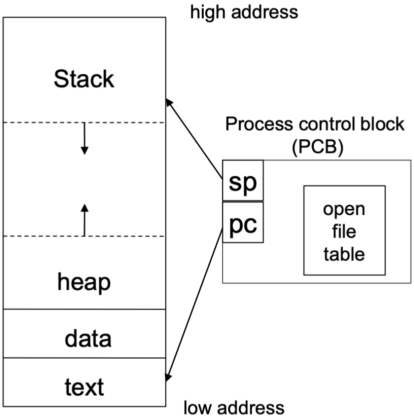
- It takes quite a bit of time to switch between processes
- Communication between processes must be done through an external structure
  - files, pipes, shared memory
- Synchronizing between processes is cumbersome.
- Is there another model that will solve these problems?

Processes



- Each process has its own
  - program counter
  - stack
  - stack pointer
  - address space
- Processes may share
  - open files
  - pipes

What is a process?

- OS abstraction for execution
- Running instance of a program

What is a process?

- OS abstraction for execution
- Running instance of a program
- Components of a process:
  - Address space
  - Code and data
  - Stack
  - Program Counter (PC)
  - Set of registers
  - Set of OS resources: open files, network connections...

Rethinking Processes

- What is similar in cooperating processes?
  - They all share the same code and data (address space)
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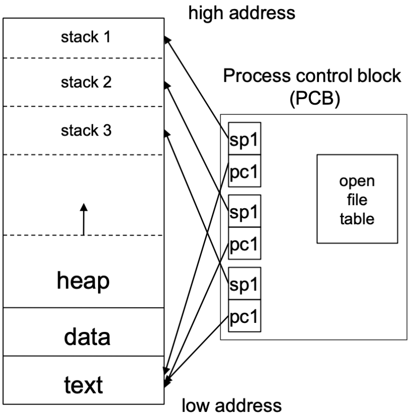
  - Each has its own execution state: PC, SP, and registers
- Key idea: Why don't we separate the concept of a process from its execution state?
  - Process: address space, privileges, resources, etc.
  - Execution state: PC, SP, registers
- *Execution state* also called thread of control, or thread

Threads



- Each thread has its own
  - program counter
  - stack
  - stack pointer
- Threads share
  - address space
    - variables
    - code
  - open files

What is a Thread?

- A **thread** is a single control flow through a program
  - What is a "control flow"?
  - How is control flow represented?
- A program with *multiple control flows* is **multithreaded**

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Control Flow

- Control includes all of the values that select which instructions in a program are executed.
- Control flow, then, is the sequence of instructions being executed.
- The hardware uses the program counter (PC) and stack to make control flow decisions.

Threads – Advantages

- Communication between threads is cheap
  - they can share variables!
- Threads are "lightweight"
  - faster to create
  - faster to switch between

Producer/Consumer Problem

- Simple example:
  `who | wc -l`
- Both the writing process (`who`) and the reading process (`wc`) of a pipeline execute concurrently.
- A pipe is usually implemented as an internal OS buffer.
- It is a resource that is **concurrently** accessed by the reader and the writer, so it must be managed carefully.

Producer/Consumer

- consumer should be blocked when buffer is empty
- producer should be blocked when buffer is full
- producer and consumer should run independently as far as buffer capacity and contents permit
- producer and consumer should never be updating the buffer at the same instant (otherwise data integrity cannot be guaranteed)
- producer/consumer is a harder problem if there are more than one consumer and/or more than one producer.

Pthreads

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POSIX: Portable Operating System-(ix)
a set of formal descriptions that provide a standard for the design of operating systems, especially ones which are compatible with Unix.

pthread_create

```
int pthread_create(pthread_t *tid,  pthread_attr_t *attr,
  void *(*func)(void*), void *arg);
```

- tid uniquely identifies a thread within a process and is returned by the function
- attr sets attributes such as priority, initial stack size
  - can be specified as NULL to get defaults
- func – the function to call to start the thread
  - accepts one void *argument, returns void *
- arg is the argument to func
- returns 0 if successful, a positive error code if not
- does not set errno but returns compatible error codes
- can use strerror() to print error messages

pthread_join

```
int pthread_join(pthread_t tid, void **status)
```

- `tid` – the tid of the thread to wait for
  - cannot wait for any thread (as in `wait()`)
- `status`, if not NULL returns the `void *` returned by the thread when it terminates.
- a thread can terminate by
  - returning from func
  - the `main()` function exiting
  - `pthread_exit()`

More `pthread` Functions

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  - it becomes a daemon thread
- `pthread_t pthread_self(void)`
  - returns the thread ID of the thread which called it
  - often see `pthread_detach(pthread_self())`

Passing Arguments to Threads

```
pthread_t thread_ID; int fd, result;
fd = open("afile", "r");
result = pthread_create(&thread_ID, NULL, myThreadFcn, (void *)&fd);

if (result != 0)
  printf("Error: %s\n", strerror(result));
```

- We can pass any variable (including a structure or array) to our thread function.
- It assumes the thread function knows what type it is.
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Solution,

- Use `malloc()` to create memory for the variable
  - initialize variable's value
  - pass pointer to new memory via `pthread_create()`
  - thread function releases memory when done.

Example

```c
typedef struct myArg { int fd;
  char name[25];
} MyArg;

int result;
pthread_t thread_ID;

MyArg *p = (MyArg *)malloc(sizeof(MyArg));
p->fd = fd; /* assumes fd is defined */
strncpy(p->name, "CSCB09", 7);
result = pthread_create(&threadID, NULL, myThreadFcn, (void *)p);

void *myThreadFcn(void *p) {
  MyArg *theArg = (MyArg *) p;
  write(theArg->fd, theArg->name, 7);
  close(theArg->fd);
  free(theArg);
  return NULL;
}
```

* Needs to include `-pthread` flag in compilation!

Thread-Safe Functions

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- Not Safe:

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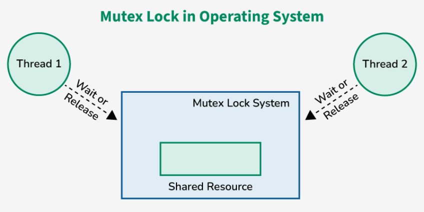
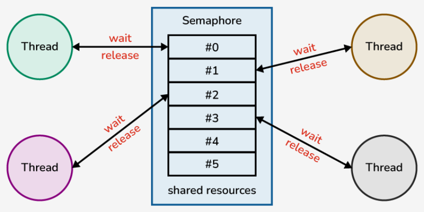
- Could use semaphores to protect access but will generally result in poor performance.

Pthread Mutexes





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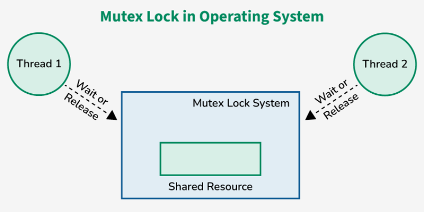
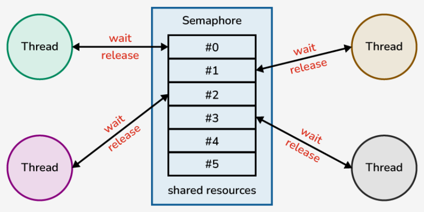





```
int pthread_mutex_init(pthread_mutex_t *mp,  const pthread_mutexattr_t *attr);

int pthread_mutex_lock(pthread_mutex_t *mp);
int pthread_mutex_trylock(pthread_mutex_t *mp);
int pthread_mutex_unlock(pthread_mutex_t *mp);
int pthread_mutex_destroy(pthread_mutex_t *mp);
```

- easier to use than `semget()` and `semop()`
- only the thread that locks a mutex can unlock it
- mutexes often declared as globals

Example

```c
///////////////////////////////////////////////

pthread_mutex_t myMutex;
int status;

status = pthread_mutex_init(&myMutex, NULL);
if(status != 0)
   printf("Error: %s \n", strerror(status));

pthread_mutex_lock(&myMutex);
/* critical section here */
pthread_mutex_unlock(&myMutex);

status = pthread_mutex_destroy(&myMutex);
if(status != 0)
  printf("Error: %s\n", strerror(status));


///////////////////////////////////////////////
```

Some final comment...

Concurrency

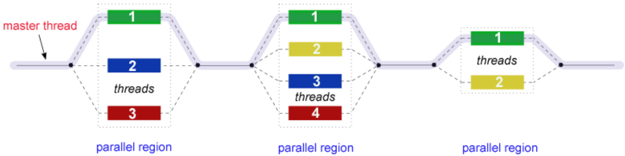
- Critical Region
- Atomic instructions
- Barrier

- Higher level abstraction
  OpenMP

OpenMP

OpenMP

- OMP uses explicit (not automatic) parallelism
- compiler-directive based
- fork-join model



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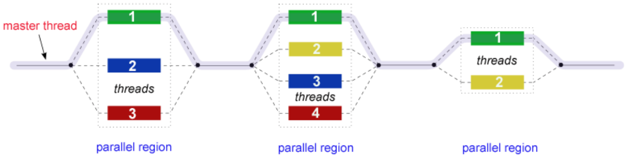


```c
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <omp.h>

int main() {

  //fork();
  #pragma omp parallel for
  for (int i=1; i<10; i++) {
    printf("hello %d from thread %d \n", i, omp_get_thread_num());
  }

  return 0;
}
```

OpenMP Example

```
#include <omp.h>

main ()  {
  int nthreads, tid;

  /* Fork a team of threads with each thread having a private tid variable */
  #pragma omp parallel private(tid) {

     /* Obtain and print thread id */
     tid = omp_get_thread_num();
     printf("Hello World from thread = %d\n", tid);

     /* Only master thread does this */
     if (tid == 0) {
        nthreads = omp_get_num_threads();
        printf("Number of threads = %d\n", nthreads);
     }

  }  /* All threads join master thread and terminate */
}
```

References and Further Resources

- Networking and IO Models
  `https://seenaburns.com/network-io/`
- Comparison of Threading Programming Models
  `https://par.nsf.gov/servlets/purl/10050480`
- POSIX-Threads and OpenMP (Shared-Memory Paradigm)
  `https://www.cs.uic.edu/~ajayk/c566/Presentation_POSIX_OpenMP.pdf`
- POSIX Threads Programming (LLNL)
  `https://hpc-tutorials.llnl.gov/posix/`

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  https://hpc-tutorials.llnl.gov/posix/

> If you are interested to learn more about shared-memory (threads) and distributed-memory (processes) parallelism, take a look at this **Fall'25 CSCD71** *"Special Topics course in HPC"*