6.087 Lecture 13 – January 28, 2010

- Review
- Multithreaded Programming
  - Race Conditions
  - Semaphores
  - Thread Safety, Deadlock, and Starvation
- Sockets and Asynchronous I/O
  - Sockets
  - Asynchronous I/O

Review: Multithreaded programming

- Thread: abstraction of parallel processing with shared memory
- Program organized to execute multiple threads in parallel
- Threads *spawned* by main thread, communicate via shared resources and *joining*
- `pthread` library implements multithreading

  - ```
    int pthread_create(pthread_t * thread, const pthread_attr_t * attr,
                       void *(*start_routine)(void *), void * arg);
    ```
  - `void pthread_exit(void *value_ptr);`
  - `int pthread_join(pthread_t thread, void **value_ptr);`
  - `pthread_t pthread_self(void);`
    ```

Review: Resource sharing

- Access to shared resources need to be controlled to ensure deterministic operation
- Synchronization objects: mutexes, semaphores, read/write locks, barriers
- Mutex: simple single lock/unlock mechanism
  - **int** pthread_mutex_init(pthread_mutex_t *mutex, **const** pthread_mutexattr_t * attr);
  - **int** pthread_mutex_destroy(pthread_mutex_t *mutex);
  - **int** pthread_mutex_lock(pthread_mutex_t *mutex);
  - **int** pthread_mutex_trylock(pthread_mutex_t *mutex);
  - **int** pthread_mutex_unlock(pthread_mutex_t *mutex);

Review: Condition variables

- Lock/unlock (with mutex) based on run-time condition variable
- Allows thread to wait for condition to be true
- Other thread signals waiting thread(s), unblocking them
  - `int pthread_cond_init(pthread_cond_t *cond, const pthread_condattr_t *attr);`
  - `int pthread_cond_destroy(pthread_cond_t *cond);`
  - `int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);`
  - `int pthread_cond_broadcast(pthread_cond_t *cond);`
  - `int pthread_cond_signal(pthread_cond_t *cond);`

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Multithreaded programming

- OS implements scheduler – determines which threads execute when
- Scheduling may execute threads in arbitrary order
- Without proper synchronization, code can execute non-deterministically
- Suppose we have two threads: 1 reads a variable, 2 modifies that variable
- Scheduler may execute 1, then 2, or 2 then 1
- Non-determinism creates a *race condition* – where the behavior/result depends on the order of execution

Race conditions

- Race conditions occur when multiple threads share a variable, without proper synchronization
- Synchronization uses special variables, like a mutex, to ensure order of execution is correct
- Example: thread T_1 needs to do something before thread T_2
  - condition variable forces thread T_2 to wait for thread T_1
  - producer-consumer model program
- Example: two threads both need to access a variable and modify it based on its value
  - surround access and modification with a mutex
  - mutex groups operations together to make them *atomic* – treated as one unit

Race conditions in assembly

Consider the following program `race.c`:

```
unsigned int cnt = 0;

void *count(void *arg) { /* thread body */
  int i;
  for (i = 0; i < 100000000; i++)
    cnt++;
  return NULL;
}

int main(void) {
  pthread_t tids[4];
  int i;
  for (i = 0; i < 4; i++)
    pthread_create(&tids[i], NULL, count, NULL);
  for (i = 0; i < 4; i++)
    pthread_join(tids[i], NULL);
  printf("cnt=%u\n",cnt);
  return 0;
}
```

What is the value of `cnt`?

[Bryant and O'Halloran. *Computer Systems: A Programmer's Perspective*. Prentice Hall, 2003.]

Race conditions in assembly

Ideally, should increment `cnt` 4×100000000 times, so `cnt` $= 400000000$. However, running our code gives:

```
athena%[1] ./race.o
cnt=137131900
athena% ./race.o
cnt=163688698
athena% ./race.o
cnt=163409296
athena% ./race.o
cnt=170865738
athena% ./race.o
cnt=169695163
```

So, what happened?

[1] Athena is MIT's UNIX-based computing environment. OCW does not provide access to it.

Race conditions in assembly

- C not designed for multithreading
- No notion of atomic operations in C
- Increment `cnt++;` maps to three assembly operations:
    1. load `cnt` into a register
    2. increment value in register
    3. save new register value as new `cnt`
- So what happens if thread interrupted in the middle?
- Race condition!

Race conditions in assembly

Let's fix our code:

```c
pthread_mutex_t mutex;
unsigned int cnt = 0;

void *count(void *arg) { /* thread body */
  int i;
  for (i = 0; i < 100000000; i++) {
    pthread_mutex_lock(&mutex);
    cnt++;
    pthread_mutex_unlock(&mutex);
  }
  return NULL;
}

int main(void) {
  pthread_t tids[4];
  int i;
  pthread_mutex_init(&mutex, NULL);
  for (i = 0; i < 4; i++)
    pthread_create(&tids[i], NULL, count, NULL);
  for (i = 0; i < 4; i++)
    pthread_join(tids[i], NULL);
  pthread_mutex_destroy(&mutex);
  printf("cnt=%u\n",cnt);
  return 0;
}
```

Race conditions

- Note that new code functions correctly, but is much slower
- C statements not atomic – threads may be interrupted at assembly level, in the middle of a C statement
- Atomic operations like mutex locking must be specified as atomic using special assembly instructions
- Ensure that all statements accessing/modifying shared variables are synchronized

Semaphores

- *Semaphore* – special nonnegative integer variable `s`, initially 1, which implements two atomic operations:
  - `P(s)` – wait until $s > 0$, decrement s and return
  - `V(s)` – increment s by 1, unblocking a waiting thread
- Mutex – locking calls `P(s)` and unlocking calls `V(s)`
- Implemented in `<semaphore.h>`, part of library `rt`, not `pthread`

Using semaphores

- Initialize semaphore to `value`:

  `int sem_init(sem_t *sem, int pshared, unsigned int value);`

- Destroy semaphore:

  `int sem_destroy(sem_t *sem);`

- Wait to lock, blocking:

  `int sem_wait(sem_t *sem);`

- Try to lock, returning immediately (0 if now locked, -1 otherwise):

  `int sem_trywait(sem_t *sem);`

- Increment semaphore, unblocking a waiting thread:

  `int sem_post(sem_t *sem);`

Producer and consumer revisited

- Use a semaphore to track available slots in shared buffer
- Use a semaphore to track items in shared buffer
- Use a semaphore/mutex to make buffer operations synchronous

Producer and consumer revisited

```c
#include <stdio.h>
#include <pthread.h>
#include <semaphore.h>

sem_t mutex, slots, items;

#define SLOTS 2
#define ITEMS 10

void* produce(void* arg)
{
  int i;
  for (i = 0; i < ITEMS; i++)
  {
    sem_wait(&slots);
    sem_wait(&mutex);
    printf("produced(%ld):%d\n",
           pthread_self(), i+1);
    sem_post(&mutex);
    sem_post(&items);
  }
  return NULL;
}

void* consume(void* arg)
{
  int i;
  for (i = 0; i < ITEMS; i++) {
    sem_wait(&items);
    sem_wait(&mutex);
    printf("consumed(%ld):%d\n",
           pthread_self(), i+1);
    sem_post(&mutex);
    sem_post(&slots);
  }
  return NULL;
}

int main()
{
  pthread_t tcons, tpro;

  sem_init(&mutex, 0, 1);
  sem_init(&slots, 0, SLOTS);
  sem_init(&items, 0, 0);

  pthread_create(&tcons,NULL,consume,NULL);
  pthread_create(&tpro,NULL,produce,NULL);
  pthread_join(tcons,NULL);
  pthread_join(tpro,NULL);

  sem_destroy(&mutex);
  sem_destroy(&slots);
  sem_destroy(&items);
  return 0;
}
```

[Bryant and O'Halloran. *Computer Systems: A Programmer's Perspective*. Prentice Hall, 2003.]

Other challenges

- Synchronization objects help solve race conditions
- Improper use can cause other problems
- Some common issues:
  - thread safety and reentrant functions
  - deadlock
  - starvation

Thread safety

- Function is *thread safe* if it always behaves correctly when called from multiple concurrent threads
- Unsafe functions fal in several categories:
  - accesses/modifies unsynchronized shared variables
  - functions that maintain state using static variables – like `rand()`, `strtok()`
  - functions that return pointers to static memory – like `gethostbyname()`
  - functions that call unsafe functions may be unsafe

Reentrant functions

- Reentrant function – does not reference any shared data when used by multiple threads
- All reentrant functions are thread-safe (are all thread-safe functions reentrant?)
- Reentrant versions of many unsafe C standard library functions exist:

Unsafe function	Reentrant version
`rand()`	`rand_r()`
`strtok()`	`strtok_r()`
`asctime()`	`asctime_r()`
`ctime()`	`ctime_r()`
`gethostbyaddr()`	`gethostbyaddr_r()`
`gethostbyname()`	`gethostbyname_r()`
`inet_ntoa()`	(none)
`localtime()`	`localtime_r()`

Thread safety

To make your code thread-safe:

- Use synchronization objects around shared variables
- Use reentrant functions
- Use synchronization around functions returning pointers to shared memory (*lock-and-copy*):
    1. lock mutex for function
    2. call unsafe function
    3. dynamically allocate memory for result; (deep) copy result into new memory
    4. unlock mutex

Deadlock

- Deadlock – happens when every thread is waiting on another thread to unblock
- Usually caused by improper ordering of synchronization objects
- Tricky bug to locate and reproduce, since schedule-dependent
- Can visualize using a progress graph – traces progress of threads in terms of synchronization objects

Deadlock

Figure removed due to copyright restrictions. Please see
http://csapp.cs.cmu.edu/public/1e/public/figures.html,
Figure 13.39, Progress graph for a program that can deadlock.

Deadlock

- Defeating deadlock extremely difficult in general
- When using only mutexes, can use the "mutex lock ordering rule" to avoid deadlock scenarios:
  A program is deadlock-free if, for each pair of mutexes (s, t) in the program, each thread that uses both s and t simultaneously locks them in the same order.

[Bryant and O'Halloran. *Computer Systems: A Programmer's Perspective* Prentice Hall, 2003.]

Starvation and priority inversion

- Starvation similar to deadlock
- Scheduler never allocates resources (e.g. CPU time) for a thread to complete its task
- Happens during priority inversion
  - example: highest priority thread T_1 waiting for low priority thread T_2 to finish using a resource, while thread T_3, which has higher priority than T_2, is allowed to run indefinitely
  - thread T_1 is considered to be in starvation

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Sockets

- *Socket* – abstraction to enable communication across a network in a manner similar to file I/O
- Uses header `<sys/socket.h>` (extension of C standard library)
- Network I/O, due to latency, usually implemented asynchronously, using multithreading
- Sockets use client/server model of establishing connections

Creating a socket

- Create a socket, getting the file descriptor for that socket:

```c
int socket(int domain, int type, int protocol);
```

  - `domain` – use constant `AF_INET`, so we're using the internet; might also use `AF_INET6` for IPv6 addresses
  - `type` – use constant `SOCK_STREAM` for connection-based protocols like TCP/IP; use `SOCK_DGRAM` for connectionless datagram protocols like UDP (we'll concentrate on the former)
  - `protocol` – specify 0 to use default protocol for the socket type (e.g. TCP)
  - returns nonnegative integer for file descriptor, or -1 if couldn't create socket
- Don't forget to close the file descriptor when you're done!

Connecting to a server

- Using created socket, we connect to server using:

```
int connect(int fd, struct sockaddr *addr, int addr_len);
```

  - `fd` – the socket's file descriptor
  - `addr` – the address and port of the server to connect to; for internet addresses, cast data of type `struct sockaddr_in`, which has the following members:
    - `sin_family` – address family; always `AF_INET`
    - `sin_port` – port in network byte order (use `htons()` to convert to network byte order)
    - `sin_addr.s_addr` – IP address in network byte order (use `htonl()` to convert to network byte order)
  - `addr_len` – size of `sockaddr_in` structure
  - returns 0 if successful

Associate server socket with a port

- Using created socket, we bind to the port using:

```c
int bind(int fd, struct sockaddr *addr, int addr_len);
```

  - `fd`, `addr`, `addr_len` – same as for `connect()`
  - note that address should be IP address of desired interface (e.g. `eth0`) on local machine
  - ensure that port for server is not taken (or you may get "address already in use" errors)
  - return 0 if socket successfully bound to port

Listening for clients

- Using the bound socket, start listening:

```
int listen(int fd, int backlog);
```

  - `fd` – bound socket file descriptor
  - `backlog` – length of queue for pending TCP/IP connections; normally set to a large number, like 1024
  - returns 0 if successful

Accepting a client's connection

- Wait for a client's connection request (may already be queued):

```
int accept(int fd, struct sockaddr *addr, int *addr_len);
```

  - `fd` – socket's file descriptor
  - `addr` – pointer to structure to be filled with client address info (can be NULL)
  - `addr_len` – pointer to int that specifies length of structure pointed to by `addr`; on output, specifies the length of the stored address (stored address may be truncated if bigger than supplied structure)
  - returns (nonnegative) file descriptor for connected client socket if successful

Reading and writing with sockets

- Send data using the following functions:

```c
int write(int fd, const void *buf, size_t len);

int send(int fd, const void *buf, size_t len, int flags);
```

- Receive data using the following functions:

```c
int read(int fd, void *buf, size_t len);

int recv(int fd, void *buf, size_t len, int flags);
```

  - `fd` – socket's file descriptor
  - `buf` – buffer of data to read or write
  - `len` – length of buffer in bytes
  - `flags` – special flags; we'll just use 0
  - all these return the number of bytes read/written (if successful)

Asynchronous I/O

- Up to now, all I/O has been synchronous – functions do not return until operation has been performed
- Multithreading allows us to read/write a file or socket without blocking our main program code (just put I/O functions in a separate thread)
- Multiplexed I/O – use `select()` or `poll()` with multiple file descriptors

I/O multiplexing with `select()`

- To check if multiple files/sockets have data to read/write/etc: (include `<sys/select.h>`)

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

  - `nfds` – specifies the total range of file descriptors to be tested (0 up to `nfds`−1)
  - `readfds`, `writefds`, `errorfds` – if not NULL, pointer to set of file descriptors to be tested for being ready to read, write, or having an error; on output, set will contain a list of only those file descriptors that are ready
  - `timeout` – if no file descriptors are ready immediately, maximum time to wait for a file descriptor to be ready
  - returns the total number of set file descriptor bits in all the sets
- Note that `select()` is a blocking function

I/O multiplexing with `select()`

- `fd_set` – a mask for file descriptors; bits are set (“1”) if in the set, or unset (“0”) otherwise
- Use the following functions to set up the structure:
  - FD_ZERO(&fdset) – initialize the set to have bits unset for all file descriptors
  - FD_SET(fd, &fdset) – set the bit for file descriptor `fd` in the set
  - FD_CLR(fd, &fdset) – clear the bit for file descriptor `fd` in the set
  - FD_ISSET(fd, &fdset) – returns nonzero if bit for file descriptor `fd` is set in the set

I/O multiplexing using `poll()`

- Similar to `select()`, but specifies file descriptors differently: (include `<poll.h>`)

```c
int poll(struct pollfd fds[], nfds_t nfds, int timeout);
```

  - `fds` – an array of `pollfd` structures, whose members `fd`, `events`, and `revents`, are the file descriptor, events to check (OR-ed combination of flags like `POLLIN`, `POLLOUT`, `POLLERR`, `POLLHUP`), and result of polling with that file descriptor for those events, respectively
  - `nfds` – number of structures in the array
  - `timeout` – number of milliseconds to wait; use 0 to return immediately, or -1 to block indefinitely

Summary

- Multithreaded programming
  - race conditions
  - semaphores
  - thread safety
  - deadlock and starvation
- Sockets, asynchronous I/O
  - client/server socket functions
  - `select()` and `poll()`

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