Concurrency: Races and Locking

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Administrivia

- Short week this week
  - Wed lecture cancelled (but OH available in AND 223 at 11:30)
  - 🦃 Fri holiday 🦃
- HW4 due in 1 ½ weeks (12/05)
- Ex 17 (🎉last🎉 exercise!!) out, due Wednesday

Some Common hw4 Bugs ☹

- Your server works, but is really, really slow
  - Check the 2nd argument to the `QueryProcessor` constructor

- Funny things happen after the first request
  - Make sure you're not destroying the `HTTPConnection` object too early (*e.g.* falling out of scope in a while loop)

- Bikeapalooza not loading properly
  - Check that you are handling all necessary file types. (can use the developer console in a web browser to check this)

- Server crashes on a blank request
  - Make sure that you handle the case that **`read`**`()` (or **`WrappedRead`**`()`) returns `0`

Lecture Outline

- **Threads: Cleanup and Data Races**
- `pthreads` and Locks
- Other Concurrency Techniques

pthread API Review

output

// thread descriptor //

- ```
  int pthread_create(
            pthread_t* thread,
            const pthread_attr_t* attr,
            void* (*start_routine)(void*),
            void* arg);
  ```
  - Creates a new thread, stores a thread id in `*thread`
  - Returns **0** on success and an error number on error (can check against error constants)
  - The new thread runs **`start_routine`**`(arg)`
- ```
  void pthread_exit(void* retval);
  ```
  - Equivalent of **`exit`**`(retval);` for a thread instead of a process
  - The thread will automatically exit once it returns from **`start_routine`**`()`

pthread API review

ID Ret

- `int pthread_join(pthread_t thread, void** retval);`
  - Waits for the thread specified by `thread` to terminate
  - The thread equivalent of `waitpid()`
  - The exit status of the terminated thread is placed in `**retval`

- `int pthread_detach(pthread_t thread);`
  - Mark thread specified by `thread` as detached – it will clean up its resources as soon as it terminates

pthread Demos

- See `pthread.c`
  - Notice how we manage memory
    - When do we allocate deallocate memory?
    - How do we pass possession of memory to threads?

- See `exit_thread.c`
  - Do we need to join every thread we create?

Data Races

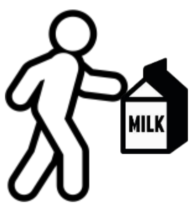
- a data race occurs when two or more different threads access the same location, at least one thread changes that memory, and they occur one after another
  - Means that the result of a program can vary depending on chance (which thread ran first?)

Data Race Example

- If your fridge has no milk, then go out and buy some more
  - What could go wrong?

```
if (!milk) {
  buy milk
}
```

- If you live alone:



- If you live with a roommate:

Poll Everywhere pollev.com/cse333

Data Race Example

- Idea: leave a note!
  - Does this fix the problem?

```
if (!note) {
  if (!milk) {
    leave note
    buy milk
    remove note
  }
}
```

A. Yes, problem fixed

B. No, could end up with no milk

C. No, could still buy multiple milks

D. We're lost…

Threads and Data Races

- Data races might interfere in painful, non-obvious ways, depending on the specifics of the data structure
- Example: two threads try to read from and write to the same shared memory location
  - Could get "correct" answer
  - Could accidentally read old value
  - One thread's work could get "lost"
- Example: two threads try to push an item onto the head of the linked list at the same time
  - Could get "correct" answer
  - Could get different ordering of items
  - Could break the data structure! ☠

Lecture Outline

- Difficulties with Threads: Cleanup and Data Races
- **`pthreads` and Locks**
- Other Concurrency Techniques

Synchronization

- Synchronization is the act of preventing two (or more) concurrently running threads from interfering with each other when operating on shared data
  - Need some mechanism to coordinate the threads
    - "Let me go first, then you can go"
  - Many different coordination mechanisms have been invented (see CSE 451)

- Goals of synchronization:
  - Safety – avoid unintended interactions with shared data structures (informally: "nothing bad happens")
  - Liveness – ability to execute in a timely manner (informally: "something good happens")

Lock Synchronization

- Use a "Lock" to grant access to a *critical section* so that only one thread can operate there at a time
  - Executed in an uninterruptible (*i.e.* atomic) manner

- Lock Acquire
  - Wait until the lock is free, then take it

- Lock Release
  - Release the lock
  - If other threads are waiting, wake exactly one up to pass lock to

- Pseudocode:

```
// non-critical code

lock.acquire();   // loop/idle if locked
// critical section
lock.release();

// non-critical code
```

Milk Example – What is the Critical Section?

- What if we use a lock on the refrigerator?
  - Probably overkill – what if roommate wanted to get eggs?
- For performance reasons, only put what is necessary in the critical section
  - Only lock the milk
  - But lock *all* steps that must run uninterrupted (*i.e.* must run as an atomic unit)

```
fridge.lock()
if (!milk) {
  buy milk
}
fridge.unlock()
```

↓

```
milk_lock.lock()
if (!milk) {
  buy milk
}
milk_lock.unlock()
```

pthreads and Locks

- Another term for a lock is a mutex ("mutual exclusion")
  - `pthread.h` defines datatype `pthread_mutex_t`

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

  - Initializes a mutex with specified attributes

```
int pthread_mutex_lock(pthread_mutex_t* mutex);
```

  - Acquire the lock – blocks if already locked

```
int pthread_mutex_unlock(pthread_mutex_t* mutex);
```

  - Releases the lock

```
int pthread_mutex_destroy(pthread_mutex_t* mutex);
```

  - "Uninitializes" a mutex – clean up when done

pthread Mutex Examples

- See `total.cc`
  - Data race between threads
- See `total_locking.cc`
  - Adding a mutex fixes our data race
- How does this compare to sequential code?
  - Likely *slower* – only 1 thread can increment at a time, but have to deal with checking the lock and switching between threads
  - One possible fix: each thread increments a local variable and then adds its value (once!) to the shared variable at the end
  - See `total_locking_better.cc`

C++11 Threads

- C++11 added threads and concurrency to its libraries
  - `<thread>` – thread objects
  - `<mutex>` – locks to handle critical sections
  - `<condition_variable>` – used to block objects until notified to resume
  - `<atomic>` – indivisible, atomic operations
  - `<future>` – asynchronous access to data
  - These might be built on top of `<pthread.h>`, but also might not be

Lecture Outline

- Difficulties with Threads: Cleanup and Data Races
- `pthreads` and Locks
- **Other Concurrency Techniques**

Review: Why Sequential?

- Advantages:
  - Simple to write, maintain, debug
  - The default, supported everywhere
- Disadvantages:
  - Depending on application, poor performance
    - One slow client will cause *all* others to block
    - Poor utilization of resources (CPU, network, disk)

Review: Why Concurrent Threads?

- Advantages:
  - Almost as simple to code as sequential
  - Concurrent execution with good CPU and network utilization
  - Threads can run in parallel if you have multiple CPUs/cores
  - Shared-memory communication is possible

- Disadvantages:
  - Need language and OS support for threads
  - If threads share data, you need locks or other synchronization
  - Threads can introduce overhead (technical + cognitive)
  - Threads have a “shared fate” (eg, “rogue” thread, shared limits)

Alternative: Different I/O Handling (1 of 2)

- Use asynchronous or non-blocking I/O

- Your program begins processing a task
  - When your program needs to read data to make further progress, it registers interest in the data with the OS and then switches to a different task
  - The OS handles the details of issuing the read on the disk/console/network
  - When data becomes available, the OS lets your program know

- Your program (almost never) blocks on I/O

Alternative: Different I/O Handling (2 of 2)

- But some devices can truly *block* your program
  - Remote computer may wait arbitrarily long before sending data
  - User may walk away from console

- How to use non-blocking I/O:
  - Enable non-blocking I/O on its file descriptors
  - Issue **`read`**`()` and **`write`**`()` system calls
    - If the read/write would block, the system call returns immediately
  - Ask the OS which file descriptors are readable/writeable
    - Can choose to block while no file descriptors are ready

Alternative: Processes

- What if we forked processes instead of threads?

- Advantages:
  - No shared memory between processes
  - No need for language support; OS provides `fork()`

- Disadvantages:
  - More overhead than threads during creation and context switching
  - Cannot easily share memory between processes – typically communicate through the file system