Introduction to Concurrency
CSE 333 Spring 2019

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Administrivia

- hw4 due next Thursday (6/6)
  - Yes, can still use one late day on hw4

- Exercise 17 (last one!) released Monday, due Wednesday
  - Concurrency via pthreads

- Final is Wednesday (6/12), 12:30-2:20 pm, ARC 147
  - Review Session: Sunday (6/9), 4-6:30 pm, ECE 125
  - Reference sheet was passed out in section yesterday, also available on course website
  - Two double-sided, handwritten sheets of notes allowed
  - Topic list and past finals on Exams page on website
Some Common hw4 Bugs

- Your server works, but is really, really slow
  - Check the 2\textsuperscript{nd} argument to the \texttt{QueryProcessor} constructor

- Funny things happen after the first request
  - Make sure you’re not destroying the \texttt{HTTPConnection} object too early (\textit{e.g.} falling out of scope in a while loop)

- Server crashes on a blank request
  - Make sure that you handle the case that \texttt{read()} (or \texttt{WrappedRead()}) returns 0
Outline

- Understanding Concurrency
  - Why is it useful
  - Why is it hard

- Concurrent Programming Styles
  - Threads vs. processes
  - Non-blocking I/O

- Search Server Revisited
Building a Web Search Engine

We need:

- A web index
  - A map from `<word>` to `<list of documents containing the word>`
  - This is probably *sharded* over multiple files
- A query processor
  - Accepts a query composed of multiple words
  - Looks up each word in the index
  - Merges the result from each word into an overall result set
Web Search Architecture

index file

query processor

index file

index file

client

client

client

client

client
Sequential Implementation

- Pseudocode for sequential query processor:

```plaintext
doclist Lookup(string word) {
    bucket = hash(word);
    hitlist = file.read(bucket);
    foreach hit in hitlist {
        doclist.append(file.read(hit));
    }
    return doclist;
}

main() {
    while (1) {
        string query_words[] = GetNextQuery();
        results = Lookup(query_words[0]);
        foreach word in query[1..n] {
            results = results.intersect(Lookup(word));
        }
        Display(results);
    }
}
```
Sequential Execution Timeline

- main()
- GetNextQuery()
- network I/O
- Lookup()
- file.read()
- ocean

- Lookup()
- file.read()
- whole

- Lookup()
- file.read()
- ravenous

- Display()
- results.intersect()
- disk I/O

- network I/O
- GetNextQuery()
- next query

- time
- query
Sequential Queries – Simplified

- a → Get Next Query()
- b → network I/O
- c → Lookup() → file. read()
- d → disk I/O
- e → intersect(), Display()
Sequential Queries – Simplified

The CPU is idle most of the time!

Only one I/O request at a time is “in flight”

Queries don’t run until earlier queries finish
Sequential Can Be Inefficient

- Only one query is being processed at a time
  - All other queries queue up behind the first one
- The CPU is idle most of the time
  - It is *blocked* waiting for I/O to complete
    - Disk I/O can be very, very slow
- At most one I/O operation is in flight at a time
  - Missed opportunities to speed I/O up
    - Separate devices in parallel, better scheduling of a single device, etc.
Concurrency

- A version of the program that executes multiple tasks "simultaneously" (execution times overlap)
  - Example: Our web server could execute multiple queries at the same time
    - While one is waiting for I/O, another can be executing on the CPU
  - Example: Execute queries one at a time, but issue I/O requests against different files/disks simultaneously
    - Could read from several index files at once, processing the I/O results as they arrive

- Concurrency != parallelism
  - Parallelism is executing multiple CPU instructions simultaneously
A Concurrent Implementation

- Use multiple threads or processes
  - As a query arrives, fork a new thread (or process) to handle it
    - The thread reads the query from the console, issues read requests against files, assembles results and writes to the console
    - The thread uses blocking I/O; the thread alternates between consuming CPU cycles and blocking on I/O
  - The OS context switches between threads/processes
    - While one is blocked on I/O, another can use the CPU
    - Multiple threads’ I/O requests can be issued at once
Introducing Threads

- Separate the concept of a **process** from an individual “**thread of control**”
  - Usually called a thread (or a *lightweight process*), this is a sequential execution stream within a process

- In most modern OS’s:
  - **Process**: address space, OS resources/process attributes *(shared)*
  - **Thread**: stack, stack pointer, program counter, registers *(separate)*
  - Threads are the *unit of scheduling* and processes are their *containers*; every process has at least one thread running in it
Multithreaded Pseudocode

```java
main() {
    while (1) {
        string query_words[] = GetNextQuery();
        ForkThread(ProcessQuery());
    }
}

doclist Lookup(string word) {
    bucket = hash(word);
    hitlist = file.read(bucket);
    foreach hit in hitlist
        doclist.append(file.read(hit));
    return doclist;
}

ProcessQuery() {
    results = Lookup(query_words[0]);
    foreach word in query[1..n]
        results = results.intersection(Lookup(word));
    Display(results);
}
```
Multithreaded Queries – Simplified

(still one CPU)

- **CPU 1.a**
- **CPU 1.b**
- **CPU 1.c**
- **CPU 1.d**
- **CPU 1.e**
- **I/O 1.a**
- **I/O 1.b**
- **I/O 1.c**
- **I/O 1.d**
- **I/O 1.e**

- **CPU 2.a**
- **CPU 2.b**
- **CPU 2.c**
- **CPU 2.d**
- **CPU 2.e**
- **I/O 2.a**
- **I/O 2.b**
- **I/O 2.c**
- **I/O 2.d**

- **CPU 3.a**
- **CPU 3.b**
- **CPU 3.c**
- **CPU 3.d**
- **CPU 3.e**
- **I/O 3.a**
- **I/O 3.b**
- **I/O 3.c**
- **I/O 3.d**

- **time**

- Query 1 (thread 1)
- Query 2 (thread 2)
- Query 3 (thread 3)

**No overlap!** CPU has to switch between threads.
Why Threads?

- **Advantages:**
  - You (mostly) write sequential-looking code
  - Threads can run in parallel if you have multiple CPUs/cores

- **Disadvantages:**
  - If threads share data, you need locks or other synchronization
    - Very bug-prone and difficult to debug
  - Threads can introduce overhead
    - Lock contention, context switch overhead, and other issues
  - Need language support for threads
Alternative: Processes

- What if we forked processes instead of threads?

- Advantages:
  - No shared memory between processes (don't worry about synchronization)
  - 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
Alternate: Different I/O Handling

- Use **asynchronous** or **non-blocking** I/O

- Your program begins processing a query
  - 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 query
  - The OS handles the details of issuing the read on the disk, or waiting for data from the console (or other devices, like the network)
  - When data becomes available, the OS lets your program know

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

- Reading from the network can truly block your program
  - Remote computer may wait arbitrarily long before sending data

- Non-blocking I/O (network, console)
  - Your program enables non-blocking I/O on its file descriptors
  - Your program issues `read()` and `write()` system calls
    - If the read/write would block, the system call returns immediately
  - Program can ask the OS which file descriptors are readable/writeable
    - `select()` or `poll()`
    - Program can choose to block while no file descriptors are ready
Outline (next two lectures)

- We’ll look at different `searchserver` implementations
  - Sequential
  - Concurrent via dispatching threads – `pthread_create()`
  - Concurrent via forking processes – `fork()`
  - Concurrent via non-blocking, event-driven I/O – `select()`
    - We won’t get to this 😞

Sequential

- Pseudocode:

```c
listen_fd = Listen(port);

while (1) {
    client_fd = accept(listen_fd);
    buf = read(client_fd);
    resp = ProcessQuery(buf);
    write(client_fd, resp);
    close(client_fd);
}
```

- See `searchserver_sequential/`
Why Sequential?

- **Advantages:**
  - Super(?) simple to build/write

- **Disadvantages:**
  - Incredibly poor performance
    - One slow client will cause *all* others to block
    - Poor utilization of resources (CPU, network, disk)
Threads

 Threads are like lightweight processes
  ▪ They execute concurrently like processes
    • Multiple threads can run simultaneously on multiple CPUs/cores
  ▪ Unlike processes, threads cohabitate the same address space
    • Threads within a process see the same heap and globals and can communicate with each other through variables and memory
      – But, they can interfere with each other – need synchronization for shared resources
    • Each thread has its own stack
Threads and Address Spaces

Before creating a thread

- One thread of execution running in the address space
  - One PC, stack, SP
- That main thread invokes a function to create a new thread
  - Typically `pthread_create()`
Threads and Address Spaces

- After creating a thread
  - *Two* threads of execution running in the address space
    - Original thread (parent) and new thread (child)
    - New stack created for child thread
    - Child thread has its own values of the PC and SP
  - Both threads share the other segments (code, heap, globals)
    - They can cooperatively modify shared data
POSIX Threads (pthreads)

- The POSIX APIs for dealing with threads
  - Part of the standard C/C++ libraries, declared in `pthread.h`
  - To enable support for multithreading, must include `-pthread` flag when compiling and linking with `gcc` command:
    ```
    gcc -Wall -std=c++11 -pthread -o foo foo.cc
    ```
Creating and Terminating Threads

- **pthread_create**
  
  ```c
  int pthread_create(
      pthread_t* thread,
      const pthread_attr_t* attr,
      void* (*start_routine)(void*),
      void* arg);
  ```

  - Creates a new thread, whose identifier is place in *thread, with attributes *attr (NULL means default attributes)
  - Returns 0 on success and an error number on error (can check against error constants)
  - The new thread runs **start_routine**(arg)

- **pthread_exit**
  
  ```c
  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**()