CSE 333
Lecture 21 -- fork, pthread_create

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HW4 is due Wednesday night
- `<panic>` if you haven’t started yet `</panic>`
- Usual late days apply *if* you have any left

pthreads exercise due Monday before class

Second exam last day of class, next Friday
- Overview/review in section next week
- Topic list and old exams on web now
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)

Server crashes on blank request
- make sure you handle the case that read( ) [or WrappedRead] returns 0
Previously

We implemented hw3 searchserver, but it was sequential

- it processed requests one at a time, in spite of client interactions blocking for arbitrarily long periods of time
  - this led to terrible performance

Servers should be concurrent

- process multiple requests simultaneously
  - issue multiple I/O requests simultaneously
  - overlap the I/O of one request with computation of another
  - utilize multiple CPUs / cores
Today

We’ll go over three versions of searchserver
- sequential
- concurrent
  - processes [fork( )]
  - threads [pthread_create( )]

Alternative (which we won’t get to): non-blocking, event driven version
  - non-blocking I/O [select( )]

Reference: Computer Systems: A Programmer’s Perspective
- 351 textbook, good source for process/thread/OS ideas
Sequential

pseudocode:

```plaintext
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);
}
```

look at searchserver_sequential/
Whither sequential?

Benefits
- super simple to build

Disadvantages
- incredibly poorly performing
  - one slow client causes all others to block
  - poor utilization of network, CPU
fork()

```c
pid_t fork(void);
```

Fork is used to create a new process (the “child”) that is an exact clone of the current process (the “parent”)

- everything is cloned (except threads)
  - all variables, file descriptors, open sockets, etc.
  - the heap, the stack, etc.

- primarily used in two patterns
  - servers: fork a child to handle a connection
  - shells: fork a child, which then exec’s a new program
fork() and address spaces

Remember this picture...?

- a process executes within an **address space**
- the address space includes:
  - a stack (for stack frames)
  - heap (for dynamically allocated data)
  - text segment (containing code)
  - etc.
fork() and address spaces

Fork causes the OS to clone the address space, creating a brand new process

- the new process starts life as a copy the old process in (nearly) every way

- the copies of the heap, stack, text segment, etc. are (nearly) identical

- the new process has copies of the parent’s data structures, stack-allocated variables, open file descriptors, and so on
fork() has peculiar semantics

- the parent invokes fork()
- the operating system clones the parent
- both the parent and the child return from fork
  - parent receives child’s pid
  - child receives a “0” as pid
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fork()
Concurrency with processes

The *parent* process blocks on `accept()` , waiting for a new client to connect

- when a new connection arrives, the parent calls `fork()` to create a *child* process
- the child process handles that new connection, and `exit()`'s when the connection terminates

Remember that children become “zombies” after death

- option a) parent calls `wait()` to “reap” children
- option b) use the double-fork trick
Graphically
Graphically

client

server
Graphically

client

connect

server
Graphically
Graphically
Graphically

client  ----->  server

server  <---- server

card exit()'s  /  parent wait()'s
Graphically

- Client
- Server

Parent closes its client connection
Graphically

client ---|--- server

server
Graphically

- Client
- Server
  - Server
  - Server
  - Server
  - Fork (child)
  - Fork (grandchild)
  - Exit ()
Graphically

client ➔ server ➔ client ➔ server ➔ client ➔ server
Graphically
Concurrent with processes

look at searchserver_processes
Whither concurrent processes?

Benefits

- almost as simple as sequential
  - in fact, most of the code is identical!
- parallel execution; good CPU, network utilization

Disadvantages

- processes are heavyweight
  - relatively slow to fork
  - context switching latency is high
- communication between processes is complicated
How slow is fork?

run forklatency.cc
Implications?

0.25 ms per fork

- maximum of \((1000 / 0.25) = 4,000\) connections per second per core
- \(~0.5\) billion connections per day per core
  
  ▶ fine for most servers
  
  ▶ too slow for a few super-high-traffic front-line web services
  
  • Facebook serves \(O(750\) billion\) page views per day
  
  • would need 3,000 -- 6,000 cores just to handle \(fork()\), i.e., without doing any work for each connection!
Threads are like lightweight processes

- like processes, they execute concurrently
  - multiple threads can run simultaneously on multiple cores/CPUs
- unlike processes, threads cohabit the same address space
  - the threads within a process see the same heap and globals
    - threads can communicate with each other through variables
    - but, threads can interfere with each other: need synchronization
  - each thread has its own stack
threads and the address space

Pre-thread create

- one thread of execution running in the address space
  - the “main” thread
  - therefore, one stack, SP, PC
- that main thread invokes a function to create a new thread
  - typically “pthread_create( )”
threads and the address space

Post- thread create
- two threads of execution running in the address space
  ‣ the “main” thread (parent)
  ‣ the child thread
  ‣ thus, two stacks, SPs, PCs
- both threads share the heap and text segment (globals)
  ‣ they can cooperatively modify shared data
threads

see thread_example.cc
Concurrent server with threads

A single *process* handles all of the connections

- but, a parent *thread* forks (or dispatches) a new thread to handle each connection

- the child thread:
  - handles the new connection
  - exits when the connection terminates
Graphically

server

accept( )
Graphically
Graphically

server

accept()
Graphically

client → pthread_create() → server

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Graphically
Graphically

client

client

server

pthread_create()
Graphically
Concurrent with threads

look at searchserver_threads/
Whither concurrent threads?

**Benefits**

- straight-line code
  - still the case that much of the code is identical to sequential!
- parallel execution; good CPU, network utilization
  - lower overhead than processes
- shared-memory communication is possible

**Disadvantages**

- *synchronization* is complicated
- shared fate within a process; one rogue thread can hurt you badly
How fast is pthread_create?

run threadlatency.cc
Implications?

0.036 ms per thread create; ~10x faster than process forking

- maximum of \((1000 / 0.018) = \sim60,000\) connections per second
- \sim10 billion connections per day per core
  
  ▶ much better

But, writing safe multithreaded code can be serious voodoo
Thread Pools

In real servers we’d like to avoid overhead needed to create a new thread or process for every request

Idea: thread pools

- Create a set of worker threads or processes on server startup, put them in a queue
- When a request arrives, remove the first worker thread from the queue and assign it to handle the request
- When a worker is done it places itself back on the queue and then sleeps until dequeued and handed a new request
Threads and races

What happens if two threads try to mutate the same data structure?

- they might interfere in painful, non-obvious ways, depending on the specifics of the data structure
  ▶ imagine if two threads try to push an item onto the head of the linked list at the same time
  ▶ depending on how the threads interleave, you might end up with a correct answer, or you might break the data structure altogether
Simple “race” example

If no milk, buy some more
- liveness: if out, somebody buys
- safety: at most one person buys

What happens with multiple threads?

if (!milk) {
    buy milk
}
Simple “race” example

Does this fix the problem?

```java
if (!note) {
    if (!milk) {
        leave note
        buy milk
        remove note
    }
}
```
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 go"
- Many different coordination mechanisms have been invented
  - Take CSE451 for details
Locks

**lock acquire**
- wait until the lock is free, then take it

**lock release**
- release the lock
- if other threads are waiting for it
  ‣ wake up exactly one of them
  ‣ give it the lock

**simplifies concurrent code**
- prevents more than one thread from entering a critical section

```java
... non-critical code ...

lock.acquire();
critical section
lock.release();

... non-critical code ...
```
Simple “race” solution

What is the critical section?
- checking for milk
- buying more milk if out

These two steps must be uninterrupted, i.e., atomic
- solution: protect the critical section with a lock

```c
milk_lock.lock();
if (!milk) {
    buy milk
}
milk_lock.unlock();
```
pthreads and locks

`pthread_mutex_init()`
- creates a mutex (a.k.a. a lock)

`pthread_mutex_lock()`
- grabs the lock

`pthread_mutex_unlock()`
- releases the lock

see `lock_example.cc`
C++ 11 Threads

C++ 11 added threads and concurrency to the 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

Might be built on top of `<pthread.h>`, maybe not

Definitely use in C++ 11 code, but pthread will still be around for a long, long time
Exercise 1

Write a simple “proxy” server

- forks a process for each connection
- reads an HTTP request from the client
  ‣ relays that request to www.cs.washington.edu
- reads the response from www.cs.washington.edu
  ‣ relays the response to the client, closes the connection

Try visiting your proxy using a web browser :)
Exercise 2

Write a client program that:

- loops, doing “requests” in a loop. Each request must:
  ‣ connect to one of the echo servers from the lecture
  ‣ do a network exchange with the server
  ‣ close the connection
- keeps track of the latency (time to do a request) distribution
- keeps track of the throughput (requests / s)
- prints these out
See you on Wednesday!