Administrivia

Last quiz due before class Monday

HW4 is due in a week

- <panic> if you haven’t started yet </panic>
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() ]

If we have time: non-blocking, event driven version

  ‣ non-blocking I/O  [ select() ]
Sequential

pseudocode:

```
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( )

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()
Concurrenty 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

server
Graphically

client -> server
Graphically
Graphically

client

fork() child

server

server
Graphically

client

server

server

server

fork() grandchild
Graphically

client ── server
  └─ server
  └─ server

child exit()’s / parent wait()’s
Graphically

client ─── server

server

parent closes its client connection
Graphically

client → server

server
Graphically
Graphically
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 \( \frac{1000}{0.25} = 4000 \) 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 \( O(750 \text{ billion}) \) 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

<table>
<thead>
<tr>
<th></th>
<th>OS kernel [protected]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP_{parent}</td>
<td>- stack_{parent}</td>
</tr>
<tr>
<td>SP_{child}</td>
<td>- stack_{child}</td>
</tr>
<tr>
<td></td>
<td>shared libraries</td>
</tr>
<tr>
<td></td>
<td>heap (malloc/free)</td>
</tr>
<tr>
<td></td>
<td>read/write segment</td>
</tr>
<tr>
<td></td>
<td>.data, .bss</td>
</tr>
<tr>
<td>PC_{child}</td>
<td>- read-only segment</td>
</tr>
<tr>
<td>PC_{parent}</td>
<td>- .text, .rodata</td>
</tr>
</tbody>
</table>
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

client

connect

server

accept( )
Graphically
Graphically

client

pthread_create()

server
Graphically
Graphically

client

client

pthread_create()

server
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) = ~60,000 connections per second
- ~10 billion connections per day per core
  - much better

But, writing safe multithreaded code can be serious voodoo
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?

```c
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

... 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

```cpp
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`
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 Friday!

(No lecture Wednesday — extra work day for projects)