CSE 333
Lecture 21 -- fork, pthread_create

Hal Perkins
Department of Computer Science & Engineering
University of Washington
Administrivia

Last exercise due Monday before class

HW4 is due Wednesday night
- <panic> if you haven’t started yet </panic>

Second exam next Friday (last day of class)
- Review in section next week
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 \( [\text{fork()}] \)
  ‣ threads \( [\text{pthread_create()}] \)

Alternative (which we won’t get to): non-blocking, event driven version

  ‣ non-blocking I/O \( [\text{select()}] \)
Sequential

```
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( )

```
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 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
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
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
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

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

parent closes its client connection
Graphically

client -> server

server

server
Graphically

client → server

server → client

fork() child

fork() grandchild

exit()
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 \( \frac{1000}{0.25} = 4,000 \) 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 \( O(750 \text{ billion}) \) 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

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 “pthreads_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
Graphically
Graphically
Graphically

client

pthread_create()

server
Graphically
Graphically

client

client

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 \((1000 / 0.018) = \sim 60,000\) connections per second
- \sim 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?

```java
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., \textit{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`
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!