CSE 333
Lecture 21 -- fork, pthread_create

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

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

Final exam: a week from Wednesday, 2:30
- Review Q&A Tuesday, 4:30, EE 045
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()]
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);
}
```

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( ) 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
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
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( )

fork_example.cc
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

server
Graphically

- client

- server
Graphically

client

connect

server
Graphically

client

server

server

fork() child
Graphically

client → server → fork() → grandchild

server

server

server
Graphically

client ←→ server

server

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

client ———— server

server ———— 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
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
- \(\sim 0.5\) 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

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()"

OS kernel [protected]

stack

shared libraries

heap (malloc/free)

read/write segment
  .data, .bss

read-only segment
  .text, .rodata
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

client

$\text{accept()}$

server

connect
Graphically

client

server

accept()
Graphically

client

server

pthread_create()
Graphically

client

server
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 $\frac{1000}{0.018} = \approx 60,000$ 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?

```c
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

```java
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!