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>

Usual late days apply if you have any left

pthreads exercise due Wednesday morning

Please fill out course evals when they’re available

Final exam Tuesday, June 6, 2:30 pm, here

Review Q&A Monday, June 5, 4:30 pm, location tba

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 a 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 concepts
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, disks
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.

<table>
<thead>
<tr>
<th>Address Space Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xFFFFFF66F</td>
</tr>
<tr>
<td>OS kernel [protected]</td>
</tr>
<tr>
<td>SP</td>
</tr>
<tr>
<td>stack</td>
</tr>
<tr>
<td>SP</td>
</tr>
<tr>
<td>shared libraries</td>
</tr>
<tr>
<td>SP</td>
</tr>
<tr>
<td>heap (malloc/free)</td>
</tr>
<tr>
<td>SP</td>
</tr>
<tr>
<td>read/write segment</td>
</tr>
<tr>
<td>.data, .bss</td>
</tr>
<tr>
<td>SP</td>
</tr>
<tr>
<td>read-only segment</td>
</tr>
<tr>
<td>.text, .rodata</td>
</tr>
<tr>
<td>0x00000000</td>
</tr>
</tbody>
</table>
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

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**Diagram: fork()**

- **OS kernel [protected]**
  - stack
  - shared libraries
  - heap (malloc/free)
  - read/write segment `.data, .bss`
  - read-only segment `.text, .rodata`
- **parent**
- **child**

---
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()

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**both** the parent and the child return from fork

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fork( )

fork( ) has peculiar semantics

the parent invokes fork( )
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both the parent and the child return from fork

parent receives child’s pid
child receives a “0” as pid
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
Graphically

client — server
Graphically
Graphically

client

server

fork() child

server
Graphically
Graphically

client - server

child exit()’s / parent wait()’s

server
Graphically

client ─────── server

server ─── parent closes its client connection
Graphically

client  ➔  server

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 (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 served $O(750 \text{ billion})$ page views per day 4 years ago!

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

<table>
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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

- $\text{accept()}$

server
Graphically

client

connect

server

accept()
Graphically

client

server

pthread_create()
Graphically

client

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) = ~60,000 connections per second
~10 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?

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

Does this fix the problem?

```plaintext
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
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 pthreads will still be around for a long, long time (and use pthreads in current exercise)
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!