Poll Everywhere

What has been your favorite topic group so far?

A. Memory Management: pointers, references, malloc/free, new/delete, memory bugs, smart pointers
B. Data Structures: arrays, structs, containers
C. Object-Oriented Programming: classes, inheritance
D. Modularization: compilation, interfaces, templates
E. I/O: files, buffering, network programming
F. Concurrency
G. I prefer not to say
Relevant Course Information

❖ Homework 4 due Thursday (6/1) @ 11:59 pm
   ▪ Submissions accepted until Sunday (6/4) @ 11:59 pm

❖ Course evaluations due Sunday night
   ▪ Please fill them out. They help all staff members improve their skills as educators and allow us to improve the course for future offerings. 😊

❖ Final starts Monday (6/5), closes Wednesday (6/7) @ 1pm
   ▪ Ed post this evening with details

❖ Friday’s lecture will be fun!
   ▪ Writing fast(er) code, dog pictures, attempts at humor
   ▪ Competition announcement with a prize sponsored by ACE
Outline

❖ We’ll look at different searchserver implementations
  ▪ Sequential
  ▪ Concurrent via forking threads – `pthread_create()`
  ▪ Concurrent via forking processes – `fork()`
  ▪ Concurrent via non-blocking, event-driven I/O – `select()`
    • We won’t get to this 😞

Why Concurrent Processes?

❖ Advantages:
  ▪ Processes are isolated from one another
    • No shared memory between processes
    • If one crashes, the other processes keep going
  ▪ No need for language support (OS provides `fork`)

❖ Disadvantages:
  ▪ Processes are heavyweight
    • Relatively slow to fork
    • Context switching latency is high
  ▪ Communication between processes is complicated
Process Isolation

- **Process Isolation** is a set of mechanisms implemented to protect processes from each other and protect the kernel from user processes.
  - Processes have separate address spaces
  - Processes have privilege levels to restrict access to resources
  - If one process crashes, others will keep running

- Inter-Process Communication (IPC) is limited, but possible
  - Pipes via `pipe()`
  - Sockets via `socketpair()`
  - Shared Memory via `shm_open()`
Creating New Processes (Review)

- `pid_t fork();`
  - Creates a child process that is an *exact clone* (except threads) of the current/parent process
  - Child process has a separate virtual address space from the parent

- `fork()` has peculiar semantics
  - The parent invokes `fork()`
Creating New Processes (Review)

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  - The OS clones the parent
Creating New Processes (Review)

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  - Creates a child process that is an *exact clone* (except threads) of the current/parent process
  - Child process has a separate virtual address space from the parent

- **fork()** has peculiar semantics
  - The parent invokes **fork()**
  - The OS clones the parent
  - *Both* the parent and the child return from fork
    - Parent receives child’s pid
    - Child receives a 0

```
child pid
0
```

```
parent
child
OS
```
fork() and Address Spaces

- Fork causes the OS to clone the address space
  - The copies of the memory segments are (nearly) identical
  - The new process has copies of the parent’s data, stack-allocated variables, open file descriptors, etc.
Zombies (Review)

- When a process terminates, its resources (e.g., its address space) hang around as the process sits in a zombie state
  - Process terminates by `return` from `main` or calling `exit()`

- A zombie process needs to be reaped
  - Done automatically when its parent process terminates
  - Can be done explicitly by its parent process by calling `wait()` or `waitpid()`, which also returns the status code
  - If the parent process terminates before the child becomes a zombie, then `init/systemd` is responsible for reaping it

- See `fork_example.cc`
  - `ps -u` displays the user’s currently running processes
Main Uses of `fork`

- Fork a child to handle some work
  - *e.g.*, server forks to handle a new connection
  - *e.g.*, web browser forks to render a new website (for security purposes)

- Fork a child that then starts a new program via `execv`
  - *e.g.*, a shell forks and starts the program you want to run
  - *e.g.*, the 333 grading scripts `fork` and `exec` your executable

- Fork a background ("daemon") process that runs independently
How Fast is `fork()`?

- See `fork_latency.cc`

- ~0.26 milliseconds per fork*
  - maximu of (1000/0.5) = 3,800 connections/sec/core
    = ~332 million connections/day/core
    - This is fine for most servers
    - Too slow for super-high-traffic front-line web services
      - Facebook served ~750 billion page views per day in 2013!
      - Would need 2-3k cores just to handle `fork()`, i.e. without doing any work for each connection

- *Past measurements are not indicative of future performance – depends on hardware, OS, software versions, ...
- Tested on `attu4 (3/5/2022)`
How Fast is `pthread_create()`?

- See `thread_latency.cc`

- ~0.02 milliseconds per thread creation
  - ~13x faster than `fork()`
  - ∴ maximum of \( \frac{1000}{0.02} = 50,000 \) connections/sec/core
    = ~4.3 billion connections/day/core
  - Mush faster, but writing safe multithreaded code can be serious voodoo, as we’ve seen

- *Past measurements are not indicative of future performance – depends on hardware, OS, software versions, …, but will typically be an order of magnitude faster than `fork()`
- Tested on `attu4` (3/5/2022)
Concurrent Server 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

- How do we avoid zombie processes from consuming all of our memory?
  - Option A: Parent calls wait() to “reap” children
  - Option B: Use a double-fork trick
Double-fork Trick

server
Double-fork Trick

client → connect → server

server: accept()
Double-fork Trick
Double-fork Trick

```
client

server

server

server

fork() grandchild
```
Double-fork Trick

When parent `wait()`'s for child, the child will be cleaned up

// Grandchild

child `exit()`'s / parent `wait()`'s
Double-fork Trick

client <- server

server

parent closes its client connection
Double-fork Trick
Double-fork Trick

```plaintext
client

server

server

fork() child

fork() grandchild

exit()

server

server

client
```
Double-fork Trick
Double-fork Trick

![Diagram of Double-fork Trick]
What will happen when one of the grandchildren processes finishes?

A. Zombie until grandparent exits
B. Zombie until grandparent reaps
C. Zombie until init reaps
D. ZOMBIE FOREVER!!!
E. We’re lost...
Concurrent with Processes Pseudocode

- See `searchserver_processes/`

```c
... // Server set up
while (1) {
    sock_fd = accept();
    pid = fork();
    if (pid == 0) {
        // ??? process
    } else {
        // ??? process
    }
}
```
Concurrent with Processes Pseudocode

❖ See `searchserver_processes/`

```c
... // Server set up
while (1) {
    sock_fd = accept();
    pid = fork();
    if (pid == 0) {
        // Child process
    }
    else {
        // Parent process
    }
}
```
Concurrent with Processes Pseudocode

- See `searchserver_processes/`

```plaintext
... // Server set up
while (1) {
    sock_fd = accept();
    pid = fork();
    if (pid == 0) {
        // Child process
        pid = fork();
        if (pid == 0) {
            // ??? process
        }
    } else {
        // Parent process
    }
}
```
Concurrent with Processes Pseudocode

- See `searchserver_processes`/
Concurrent with Processes Pseudocode

❖ See searchserver_processes/

```c
... // Server set up
while (1) {
    sock_fd = accept();
    pid = fork();
    if (pid == 0) {
        // Child process
        pid = fork();
        if (pid == 0) {
            // Grand-child process
            HandleClient(sock_fd, ...);
        }
        // Clean up resources...
        exit();
    } else {
        // Parent process
    }
}
```
Concurrent with Processes Pseudocode

- See searchserver_processes/

```c
... // Server set up
while (1) {
    sock_fd = accept();
    pid = fork();
    if (pid == 0) {
        // Child process
        pid = fork();
        if (pid == 0) {
            // Grand-child process
            HandleClient(sock_fd, ...);
        }
        // Clean up resources...
        exit();
    } else {
        // Parent process
        // Wait for child to immediately die
        wait();
        close(sock_fd);
    }
}
```
Outline (Revisited)

❖ We’ll look at different searchserver implementations
  ▪ Sequential
  ▪ Concurrent via forking threads – `pthread_create()`
  ▪ Concurrent via forking processes – `fork()`
  ▪ Concurrent via non-blocking, event-driven I/O – `select()`

❖ Conclusions:
  ▪ Concurrent execution leads to better CPU, network utilization
  ▪ Writing concurrent software can be tricky and different concurrency methods have benefits and drawbacks

❖ In real servers, we’d like to avoid the overhead needed to create a new thread or process for every request... how?
Aside: Thread Pools

❖ Idea:
  ▪ Create a fixed set of worker threads when the server starts
  ▪ When a request arrives, add it to a queue of tasks (using locks)
  ▪ Each thread tries to remove a task from the queue (using locks)
  ▪ When a thread is finished with one task, it tries to get a new task from the queue (using locks)

❖ A thread pool is written for you in Homework 4!
  ▪ Feel free to take a look, if curious