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
Concurrency: Processes
CSE 333 Fall 2023

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Relevant Course Information

- Exercise 12 due Monday (12/4) by 10pm

- Homework 4 due Wednesday (12/6) by 10pm
  - Submissions accepted until Friday (12/8) by 10pm

- Final exam topics and samples posted on Friday
  - Will cover topics from midterm onward covered in course
  - Similar format, but longer duration than midterm (Dec. 13, 2:30pm-4:20pm)

- Friday’s lecture will be fun!
  - Writing fast(er) code, dog pictures, attempts at humor
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()`

![Diagram](image-url)
Creating New Processes (Review)

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

- \( \sim 0.26 \) milliseconds per fork*
  - \( \therefore \) maximum of \( 1000 \div 0.5 \) = 3,800 connections/sec/core
    - \( \approx 332 \) million connections/day/core
      - This is fine for most servers
      - Too slow for super-high-traffic front-line web services
        - Facebook served \( \sim 750 \) 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`

- \( \sim 0.02 \) milliseconds per thread creation*
  - \( \sim 13x \) faster than `fork()`
  - \( \therefore \) maximum of \( \frac{1000}{0.02} = 50,000 \) connections/sec/core
    - \( = \sim 4.3 \) 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 accept ()
Double-fork Trick

client

server

fork() child

server
Double-fork Trick

```
client
server
server
server
```

fork() grandchild

Diagram showing the concept of the double-fork trick, where a client communicates with a server, which itself forks to create additional servers.
Double-fork Trick

When parent wait()’s for child, the child will be cleaned up.
Double-fork Trick

- Client
- Server

- Parent closes its client connection
Double-fork Trick

client -> server

server

server
Double-fork Trick

client → server

fork() child
fork() grandchild
exit()
Double-fork Trick

client ———— server

server

client ———— server
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/`

```c
... // 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/

```cpp
... // 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, ...);
        }
    } 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
    }
}
```
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 search server implementations
  - Sequential
  - Concurrent via forking threads – `pthread_create()`
  - Concurrent via forking processes – `fork()`
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- 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