Concurrent Programming

15-213: Introduction to Computer Systems
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Instructor:
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Concurrent Programming is Hard!

- The human mind tends to be sequential
- The notion of time is often misleading
- Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible
Data Race
Deadlock
Deadlock

- Example from signal handlers.
- Why don’t we use printf in handlers?

```c
void catch_child(int signo) {
    printf("Child exited!\n"); // this call may reenter printf/puts! BAD! DEADLOCK!
    while (waitpid(-1, NULL, WNOHANG) > 0) continue; // reap all children
}

int main(int argc, char** argv) {
    ...  
    for (i = 0; i < 1000000; i++) {
        if (fork() == 0) {
            // in child, exit immediately
            exit(0);
        }
        // in parent
        sprintf(buf, "Child %d started\n", i);
        printf("%s", buf);
    }
    return 0;
}
```

![Diagram illustration of the problem]
Testing Printf Deadlock

void catch_child(int signo) {
    printf("Child exited!\n"); // this call may reenter printf/puts! BAD! DEADLOCK!
    while (waitpid(-1, NULL, WNOHANG) > 0) continue; // reap all children
}

int main(int argc, char** argv) {
    ...
    for (i = 0; i < 1000000; i++) {
        if (fork() == 0) {
            // in child, exit immediately
            exit(0);
        }
        // in parent
        sprintf(buf, "Child #%d started\n", i);
        printf("%s", buf);
    }
    return 0;
}
Liveloop
Livelock
Starvation

- Yellow must yield to green
- Continuous stream of green cars
- Overall system makes progress, but some individuals wait indefinitely
Concurrent Programming is Hard!

- Classical problem classes of concurrent programs:
  - **Races**: outcome depends on arbitrary scheduling decisions elsewhere in the system
    - Example: who gets the last seat on the airplane?
  - **Deadlock**: improper resource allocation prevents forward progress
    - Example: traffic gridlock
  - **Livelock / Starvation / Fairness**: external events and/or system scheduling decisions can prevent sub-task progress
    - Example: people always jump in front of you in line

- Many aspects of concurrent programming are beyond the scope of our course..
  - but, not all 😊
  - We’ll cover some of these aspects in the next few lectures.
Concurrent Programming is Hard!

It may be hard, but ...

it can be useful and sometimes necessary!
Reminder: Iterative Echo Server

Client

- socket
- connect
- rio_readlineb
- rio_writen
- close

Server

- socket
- bind
- listen
- accept
- rio_readlineb
- rio_writen
- close

open_clientfd

open_listenfd

Connection request

Await connection request from next client

Client / Server Session
Iterative Servers

- Iterative servers process one request at a time

Client 1

- connect
- write
- call read
- ret read
- close

Server

- accept
- read
- write
- read
- close
Iterative Servers

- Iterative servers process one request at a time

Client 1 | Server | Client 2
---|---|---
connect | accept | connect
write | read | write
call read | write | call read
ret read | read | ret read
close | close | close

Wait for server to finish with Client 1
Where Does Second Client Block?

- Second client attempts to connect to iterative server

**Client**

- `open_clientfd`
- `socket`
- `connect`
- `rio_writen`
- `rio_readlineb`
- `Connection request`

**Call to connect returns**
- Even though connection not yet accepted
- Server side TCP manager queues request
- Feature known as “TCP listen backlog”

**Call to rio_writen returns**
- Server side TCP manager buffers input data

**Call to rio_readlineb blocks**
- Server hasn’t written anything for it to read yet.
Fundamental Flaw of Iterative Servers

Solution: use *concurrent servers* instead

- Concurrent servers use multiple concurrent flows to serve multiple clients at the same time
Approaches for Writing Concurrent Servers

Allow server to handle multiple clients concurrently

1. Process-based
   - Kernel automatically interleaves multiple logical flows
   - Each flow has its own private address space

2. Event-based
   - Programmer manually interleaves multiple logical flows
   - All flows share the same address space
   - Uses technique called I/O multiplexing

3. Thread-based
   - Kernel automatically interleaves multiple logical flows
   - Each flow shares the same address space
   - Hybrid of process-based and event-based
Approach #1: Process-based Servers

- Spawn separate process for each client

**Client 1**
- Call connect
- Call fgets

**User goes out to lunch**
- Client 1 blocks waiting for user to type in data

**Server**
- Call accept
- Ret accept
- Child 1
- Call read

**Child blocks waiting for data from Client 1**
Approach #1: Process-based Servers

- Spawn separate process for each client

Client 1

- Call `connect`

User goes out to lunch

Client 1 blocks waiting for user to type in data

Child 1

- Call `fgets`

Child blocks waiting for data from Client 1

Server

- Call `accept`

Child 2

- Call `read`

- Call `accept`

Client 2

- Call `connect`

- Call `fgets`

- Call `write`

- Call `read`

- Close

...
Iterative Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        echo(connfd);
        Close(connfd);
    }
    exit(0);
}
```

- Accept a connection request
- Handle echo requests until client terminates
Making a Concurrent Echo Server

```c
int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);

        echo(connfd);  /* Child services client */
        Close(connfd); /* child closes connection with client */
        exit(0);
    }
}
```

echoserverp.c
Making a Concurrent Echo Server

```c
int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        if (Fork() == 0) {
            echo(connfd);    /* Child services client */
            Close(connfd);   /* Child closes connection with client */
            exit(0);         /* Child exits */
        }
        Close(connfd); /* Parent closes connected socket (important!) */
    }
}
```

echoserverp.c
Making a Concurrent Echo Server

```c
int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
        if (Fork() == 0) {
            echo(connfd);    /* Child services client */
            Close(connfd);   /* Child closes connection with client */
            exit(0);         /* Child exits */
        }
        Close(connfd); /* Parent closes connected socket (important!) */
    }
}
```

Why?
Making a Concurrent Echo Server

```c
int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        if (Fork() == 0) {
            Close(listenfd); /* Child closes its listening socket */
            echo(connfd); /* Child services client */
            Close(connfd); /* Child closes connection with client */
            exit(0); /* Child exits */
        }
        Close(connfd); /* Parent closes connected socket (important!) */
    }
}
```
Process-Based Concurrent Echo Server

```c
int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;

    Signal(SIGCHLD, sigchld_handler);
    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        if (Fork() == 0) {
            Close(listenfd); /* Child closes its listening socket */
            echo(connfd);    /* Child services client */
            Close(connfd);   /* Child closes connection with client */
            exit(0);         /* Child exits */
        }
        Close(connfd);   /* Parent closes connected socket (important!) */
    }
}
```

Process-Based Concurrent Echo Server (cont)

```c
void sigchld_handler(int sig)
{
    while (waitpid(-1, 0, WNOHANG) > 0)
        ;
    return;
}
```
echoserverp.c

- Reap all zombie children
Concurrent Server: `accept` Illustrated

1. Server blocks in `accept`, waiting for connection request on listening descriptor `listenfd`

2. Client makes connection request by calling `connect`

3. Server returns `connfd` from `accept`. Forks child to handle client. Connection is now established between `clientfd` and `connfd`
Process-based Server Execution Model

- Each client handled by independent child process
- No shared state between them
- Both parent & child have copies of listenfd and connfd
  - Parent must close `connfd`
  - Child should close `listenfd`
Issues with Process-based Servers

- Listening server process must reap zombie children
  - to avoid fatal memory leak
- Parent process must close its copy of connfd
  - Kernel keeps reference count for each socket/open file
  - After fork, `refcnt(connfd) = 2`
  - Connection will not be closed until `refcnt(connfd) = 0`
Pros and Cons of Process-based Servers

- + Handle multiple connections concurrently
- + Clean sharing model
  - descriptors (no)
  - file tables (yes)
  - global variables (no)
- + Simple and straightforward
- – Additional overhead for process control
- – Nontrivial to share data between processes
  - (This example too simple to demonstrate)
Approach #2: Event-based Servers

- **Server maintains set of active connections**
  - Array of connfd’s

- **Repeat:**
  - Determine which descriptors (connfd’s or listenfd) have pending inputs
    - e.g., using `select` function
    - arrival of pending input is an event
  - If listenfd has input, then accept connection
    - and add new connfd to array
  - Service all connfd’s with pending inputs

- **Details for select-based server in book**
I/O Multiplexed Event Processing

Active Descriptors

- **listenfd = 3**

<table>
<thead>
<tr>
<th>connfd’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

Pending Inputs

- **listenfd = 3**

<table>
<thead>
<tr>
<th>connfd’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>-1</td>
</tr>
</tbody>
</table>

Active Descriptors:
- **Active**
- **Inactive**
- **Never Used**

Anything happened?
Pros and Cons of Event-based Servers

- One logical control flow and address space.
- Can single-step with a debugger.
- No process or thread control overhead.
  - Design of choice for high-performance Web servers and search engines.
    - E.g., Node.js, nginx, Tornado

- Significantly more complex to code than process- or thread-based designs.
- Hard to provide fine-grained concurrency
  - E.g., how to deal with partial HTTP request headers
- Cannot take advantage of multi-core
  - Single thread of control
Break Time!

lollygag: “to waste time"

Check out:

Quiz: day 23: Concurrent programming

https://canvas.cmu.edu/courses/3822
Approach #3: Thread-based Servers

- Very similar to approach #1 (process-based)
  - ...but using threads instead of processes
Traditional View of a Process

- Process = process context + code, data, and stack

**Process context**

**Program context:**
- Data registers
- Condition codes
- Stack pointer (SP)
- Program counter (PC)

**Kernel context:**
- VM structures
- Descriptor table
- brk pointer

**Code, data, and stack**

- Stack
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data
Alternate View of a Process

- Process = thread + code, data, and kernel context

Thread (main thread)

- Stack
  - Thread context:
    - Data registers
    - Condition codes
    - Stack pointer (SP)
    - Program counter (PC)

Code, data, and kernel context

- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data
- Kernel context:
  - VM structures
  - Descriptor table
  - brk pointer

SP → brk
PC
A Process With Multiple Threads

- Multiple threads can be associated with a process
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own stack for local variables
    - but not protected from other threads
  - Each thread has its own thread id (TID)

Thread 1 (main thread)  Thread 2 (peer thread)

Thread 1 context:
- Data registers
- Condition codes
- SP₁
- PC₁

Thread 2 context:
- Data registers
- Condition codes
- SP₂
- PC₂

Shared code and data:
- shared libraries
- run-time heap
- read/write data
- read-only code/data

Kernel context:
- VM structures
- Descriptor table
- brk pointer
Logical View of Threads

- **Threads associated with process form a pool of peers**
  - Unlike processes which form a tree hierarchy

![Diagram showing threads associated with process foo and process hierarchy]
Concurrent Threads

- Two threads are *concurrent* if their flows overlap in time.
- Otherwise, they are sequential.

**Examples:**
- Concurrent: A & B, A&C
- Sequential: B & C

```
<table>
<thead>
<tr>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Thread A</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
```
Concurrent Thread Execution

- **Single Core Processor**
  - Simulate parallelism by time slicing

- **Multi-Core Processor**
  - Can have true parallelism

---

**Thread A**

---

**Thread B**

---

**Thread C**

---

**Time**

---

Run 3 threads on 2 cores
Threads vs. Processes

- How threads and processes are similar
  - Each has its own logical control flow
  - Each can run concurrently with others (possibly on different cores)
  - Each is context switched

- How threads and processes are different
  - Threads share all code and data (except local stacks)
    - Processes (typically) do not
  - Threads are somewhat less expensive than processes
    - Process control (creating and reaping) twice as expensive as thread control
      - Linux numbers:
        - ~20K cycles to create and reap a process
        - ~10K cycles (or less) to create and reap a thread
Posix Threads (Pthreads) Interface

- **Pthreads**: Standard interface for ~60 functions that manipulate threads from C programs
  - Creating and reaping threads
    - `pthread_create()`
    - `pthread_join()`
  - Determining your thread ID
    - `pthread_self()`
  - Terminating threads
    - `pthread_cancel()`
    - `pthread_exit()`
    - `exit()` [terminates all threads]
    - `return` [terminates current thread]
  - Synchronizing access to shared variables
    - `pthread_mutex_init`
    - `pthread_mutex_[un]lock`
The Pthreads "hello, world" Program

/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"
void *thread(void *vargp);

int main(int argc, char** argv)
{
    pthread_t tid;
    Pthread_create(&tid, NULL, thread, NULL);
    Pthread_join(tid, NULL);
    return 0;
}

void *thread(void *vargp) /* thread routine */
{
    printf("Hello, world!\n");
    return NULL;
}
Execution of Threaded “hello, world”

1. **Main thread**
   - Call `Pthread_create()`
   - `Pthread_create()` returns
   - Call `Pthread_join()`
   - `Pthread_join()` returns
   - `exit()`
   - Terminates main thread and any peer threads

2. **Peer thread**
   - `printf()` returns
   - `return NULL;`
   - Peer thread terminates
Thread-Based Concurrent Echo Server

```c
int main(int argc, char **argv)
{
    int listenfd, *connfdp;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;
    pthread_t tid;

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfdp = Malloc(sizeof(int));
        *connfdp = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        Pthread_create(&tid, NULL, thread, connfdp);
    }
    return 0;
}
```

- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of `Malloc()`! [but not `Free()`]
Thread-Based Concurrent Server (cont)

/* Thread routine */
void *thread(void *vargp)
{
    int connfd = *((int *)vargp);
    Pthread_detach(pthread_self());
    Free(vargp);
    echo(connfd);
    Close(connfd);
    return NULL;
}

- Run thread in “detached” mode.
  - Runs independently of other threads
  - Reaped automatically (by kernel) when it terminates
- Free storage allocated to hold connfd
- Close connfd (important!)
Thread-based Server Execution Model

- Each client handled by individual peer thread
- Threads share all process state except TID
- Each thread has a separate stack for local variables
Issues With Thread-Based Servers

- Must run “detached” to avoid memory leak
  - At any point in time, a thread is either *joinable* or *detached*
  - *Joinable* thread can be reaped and killed by other threads
    - must be reaped (with `pthread_join`) to free memory resources
  - *Detached* thread cannot be reaped or killed by other threads
    - resources are automatically reaped on termination
  - Default state is joinable
    - use `pthread_detach(pthread_self())` to make detached

- Must be careful to avoid unintended sharing
  - For example, passing pointer to main thread’s stack
    - `Pthread_create(&tid, NULL, thread, (void *)&connfd);`

- All functions called by a thread must be *thread-safe*
  - (next lecture)
while (1) {
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
    Pthread_create(&tid, NULL, thread, &connfd);
}
Could this race occur?

Main

```c
int i;
for (i = 0; i < 100; i++) {
    Pthread_create(&tid, NULL,
                   thread, &i);
}
```

Thread

```c
void *thread(void *vargp)
{
    int i = *(int *)vargp;
    Pthread_detach(pthread_self());
    save_value(i);
    return NULL;
}
```

■ Race Test

- If no race, then each thread would get different value of \( i \)
- Set of saved values would consist of one copy each of 0 through 99
Experimental Results

No Race

Single core laptop

Multicore server

The race can really happen!
Correct passing of thread arguments

```c
/* Main routine */
int *connfdp;
connfdp = Malloc(sizeof(int));
*connfdp = Accept(. . .);
Pthread_create(&tid, NULL, thread, connfdp);
```

```c
/* Thread routine */
void *thread(void *vargp)
{
    int connfd = *((int *)vargp);
    . . .
    Free(vargp);
    . . .
    return NULL;
}
```

- Producer-Consumer Model
  - Allocate in main
  - Free in thread routine
Pros and Cons of Thread-Based Designs

+ Easy to share data structures between threads
  - e.g., logging information, file cache
+ Threads are more efficient than processes

– Unintentional sharing can introduce subtle and hard-to-reproduce errors!
  - The ease with which data can be shared is both the greatest strength and the greatest weakness of threads
  - Hard to know which data shared & which private
  - Hard to detect by testing
    - Probability of bad race outcome very low
    - But nonzero!
  - Future lectures
Summary: Approaches to Concurrency

- **Process-based**
  - Hard to share resources: Easy to avoid unintended sharing
  - High overhead in adding/removing clients

- **Event-based**
  - Tedious and low level
  - Total control over scheduling
  - Very low overhead
  - Cannot create as fine grained a level of concurrency
  - Does not make use of multi-core

- **Thread-based**
  - Easy to share resources: Perhaps too easy
  - Medium overhead
  - Not much control over scheduling policies
  - Difficult to debug
    - Event orderings not repeatable