

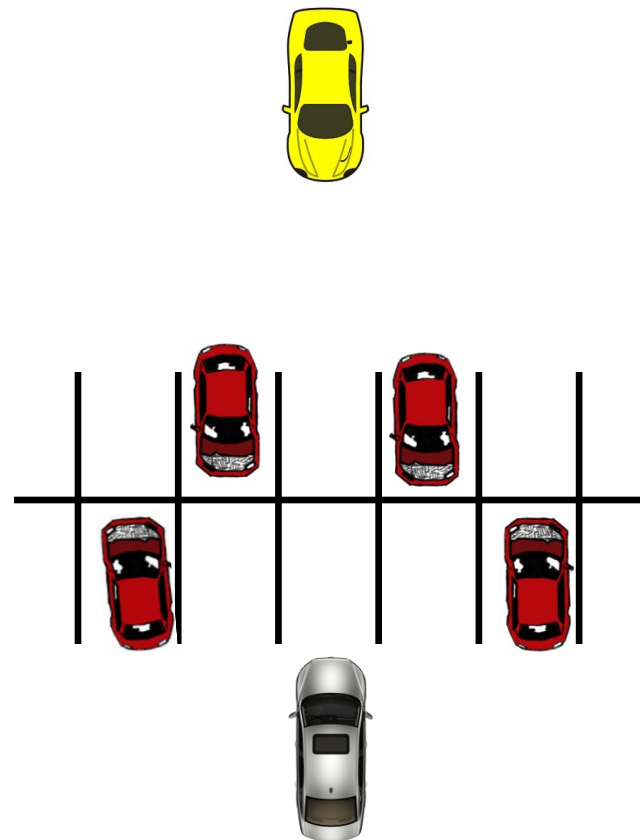
# Concurrent Programming

15-213/14-513/15-513: Introduction to Computer Systems  
23<sup>rd</sup> Lecture, April 14, 2022

# 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

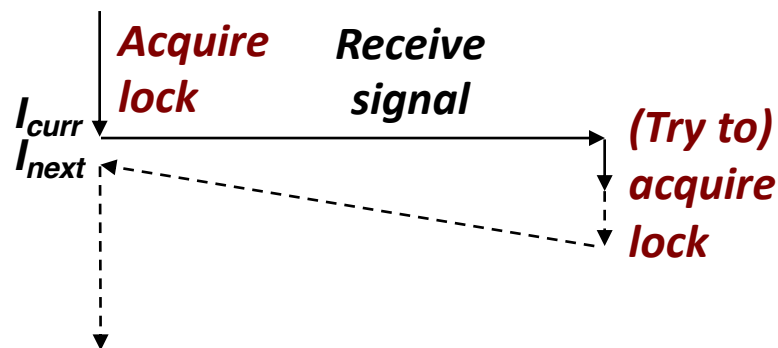


- Example from signal handlers.
- Why don't we use printf in handlers?

```
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
}
```

- **Printf code:**

- Acquire lock
- Do something
- Release lock



# Deadlock

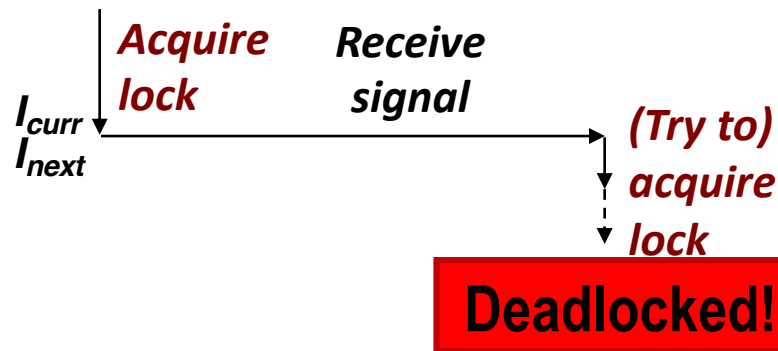


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}
```

- **Printf code:**

- Acquire lock
- Do something
- Release lock



- What if signal handler interrupts call to printf?

# Testing Printf Deadlock

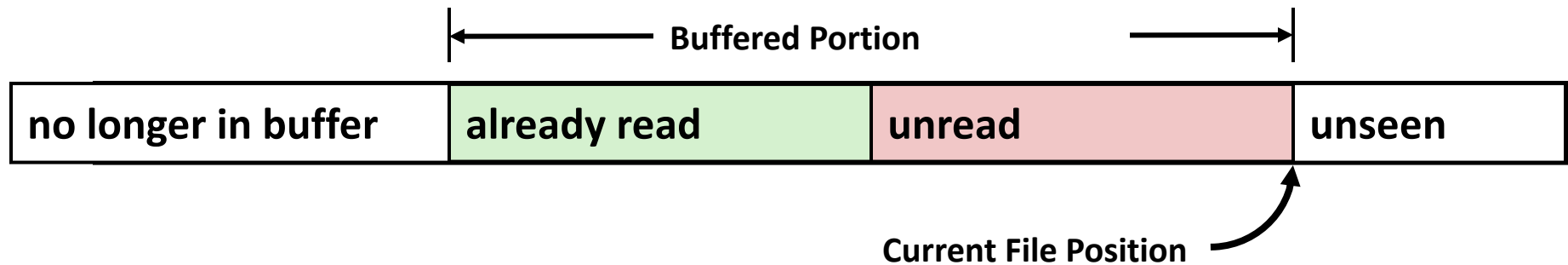
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    printf("Child exited!\n"); // this call may reenter printf/puts! BAD! DEADLOCK!
    while (waitpid(-1, NULL, WNOHANG) > 0) continue; // reap all children
}

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;
}
```

```
Child #0 started
Child #1 started
Child #2 started
Child #3 started
Child #3 started
Child exited!
Child #4 started
Child exited!
Child #5 started
.
.
.
Child #5888 started
Child #5889 started
```

# Why Does Printf require Locks?

- Printf (and fprintf, sprintf) implement *buffered* I/O



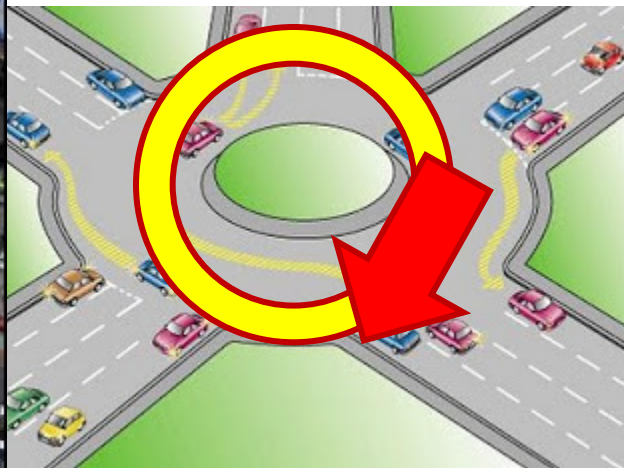
- Require locks to access the shared buffers



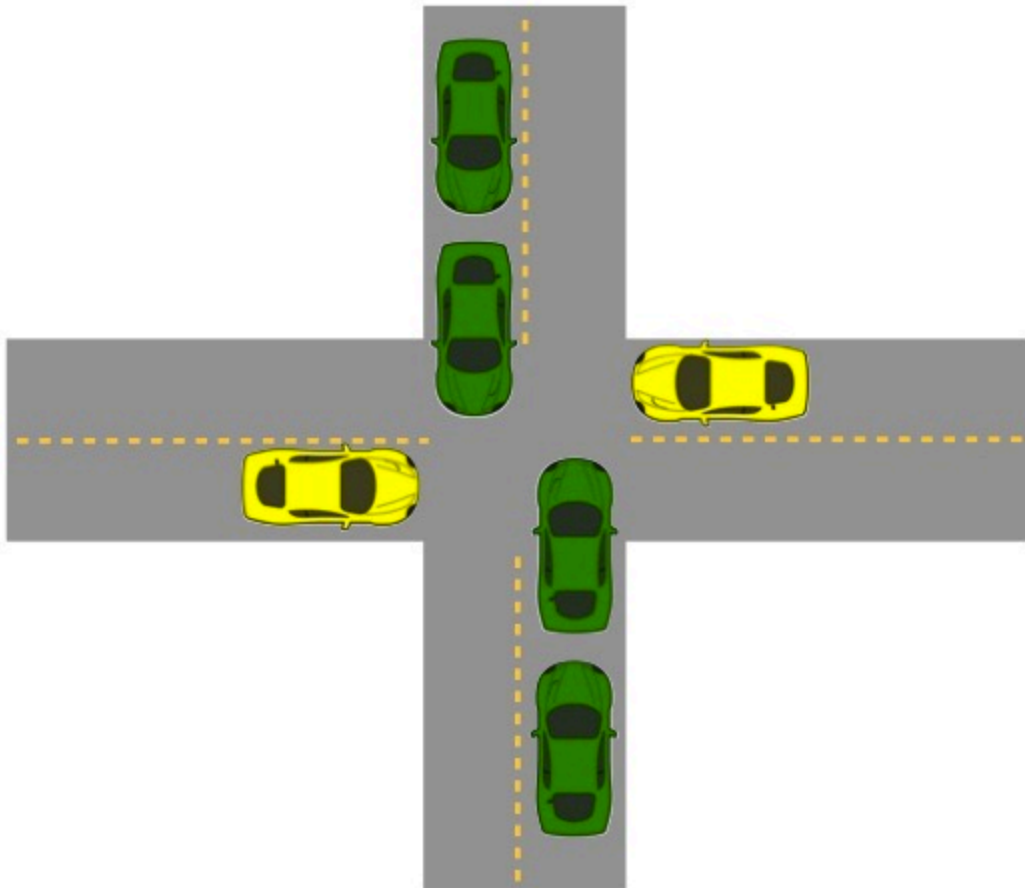
# Livelock



# 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!

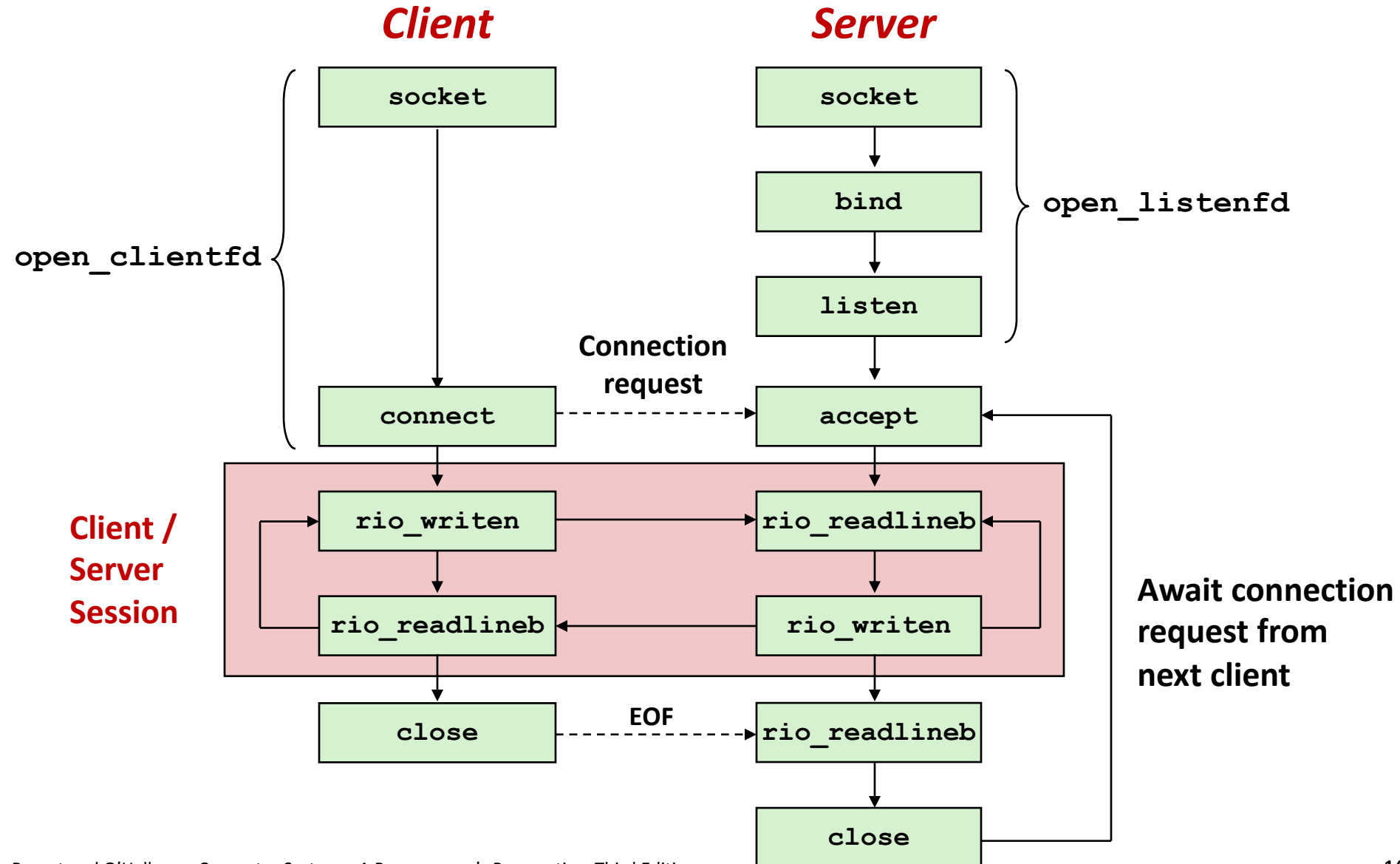
- **Classical problem classes of concurrent programs:**
  - **Races:** outcome depends on arbitrary scheduling decisions elsewhere in the system
    - Example: who gets the last seat on the airplane?
  - **Deadlock:** improper resource allocation prevents forward progress
    - Example: traffic gridlock
  - **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 ...

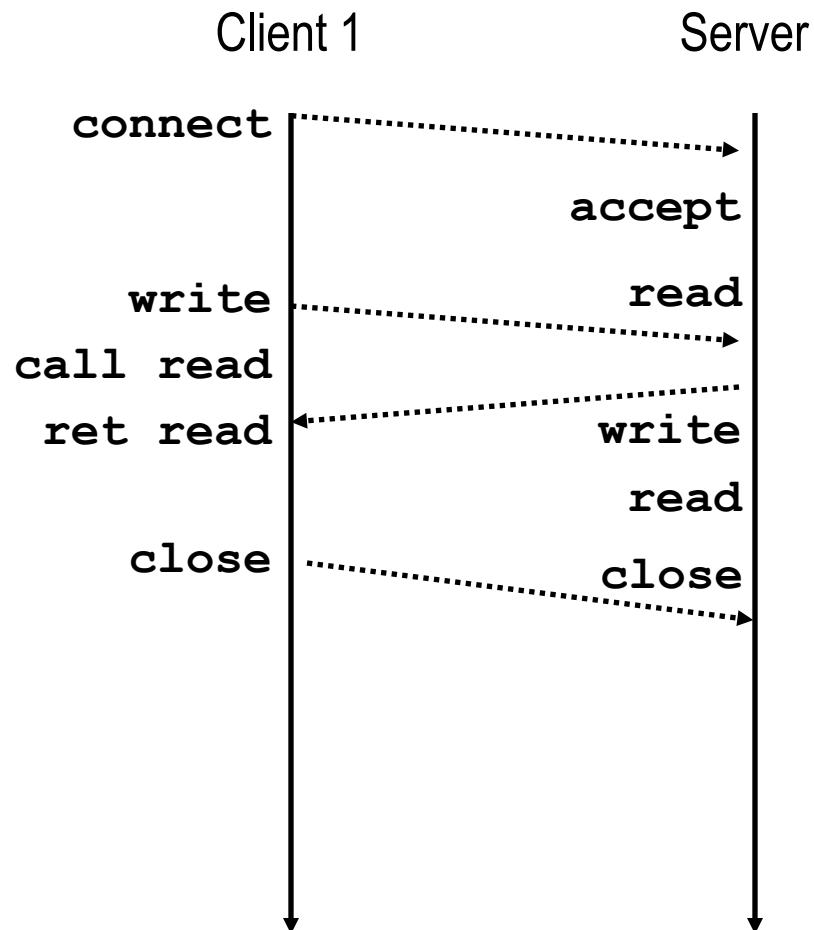
it can be useful and **more and more** necessary!

# Reminder: Iterative Echo Server



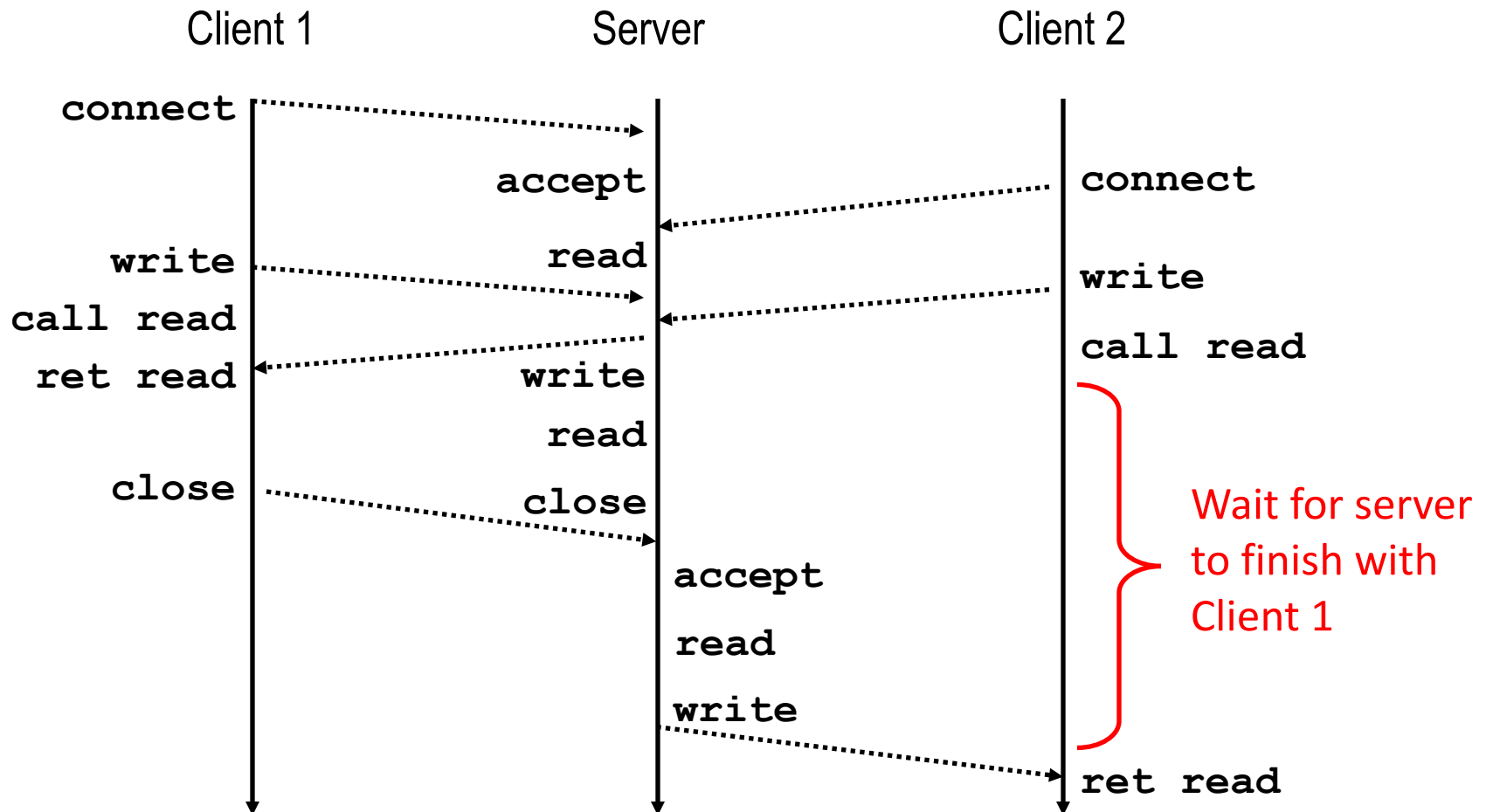
# Iterative Servers

- Iterative servers process one request at a time



# Iterative Servers

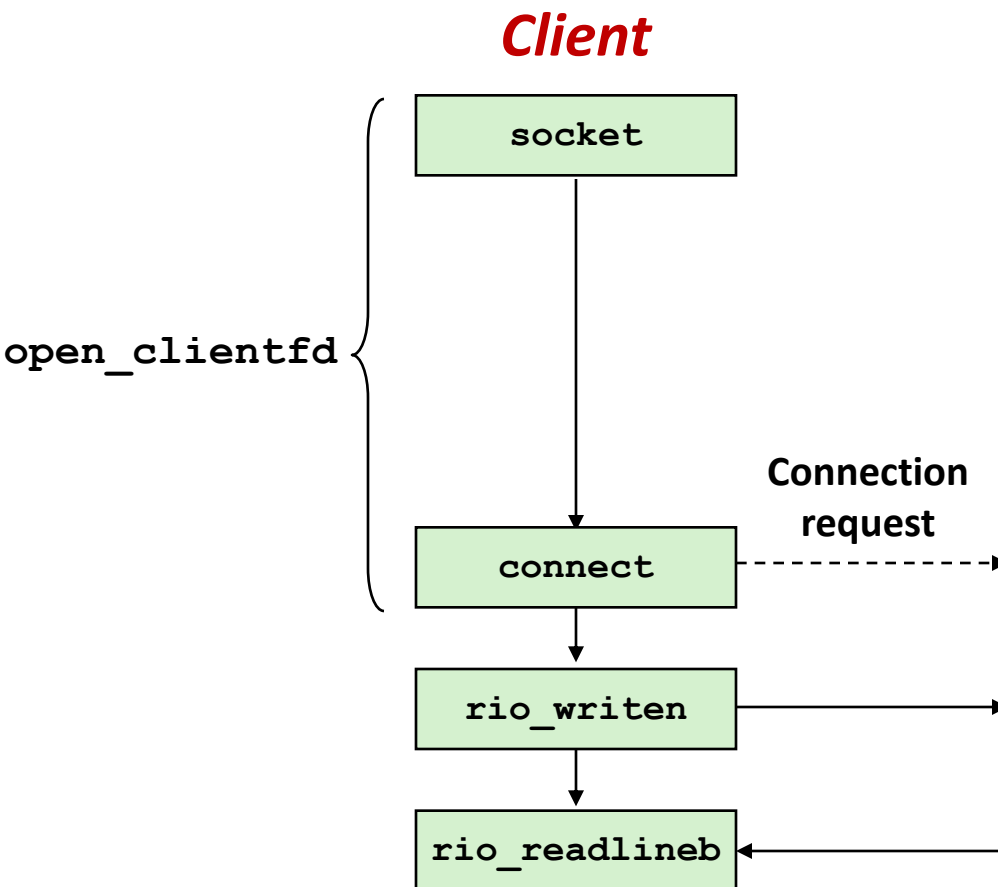
- Iterative servers process one request at a time





# Where Does Second Client Block?

- Second client attempts to connect to iterative server



- Call to `connect` returns

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

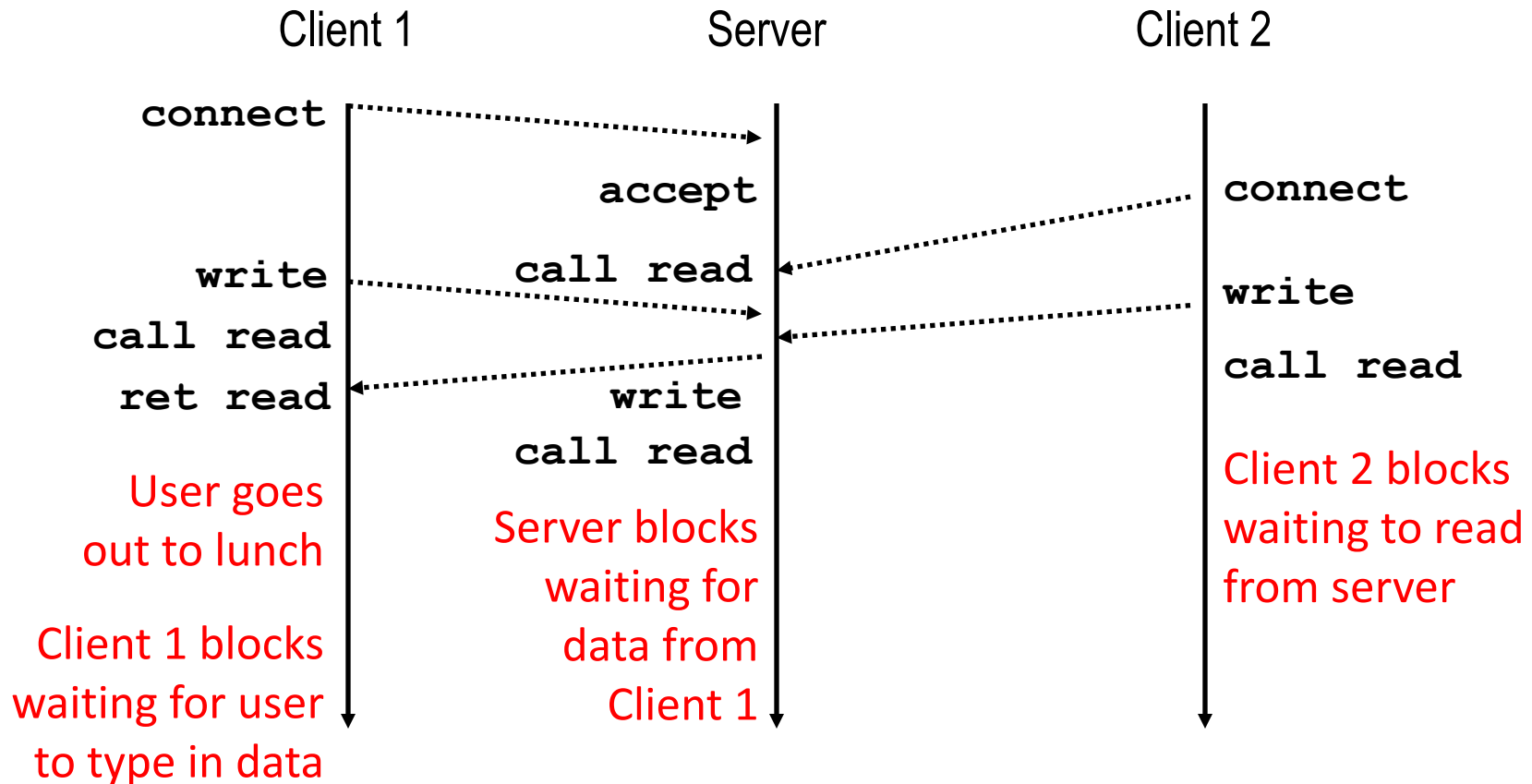
- Call to `rio_writen` returns

- 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 of process-based and event-based

# 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

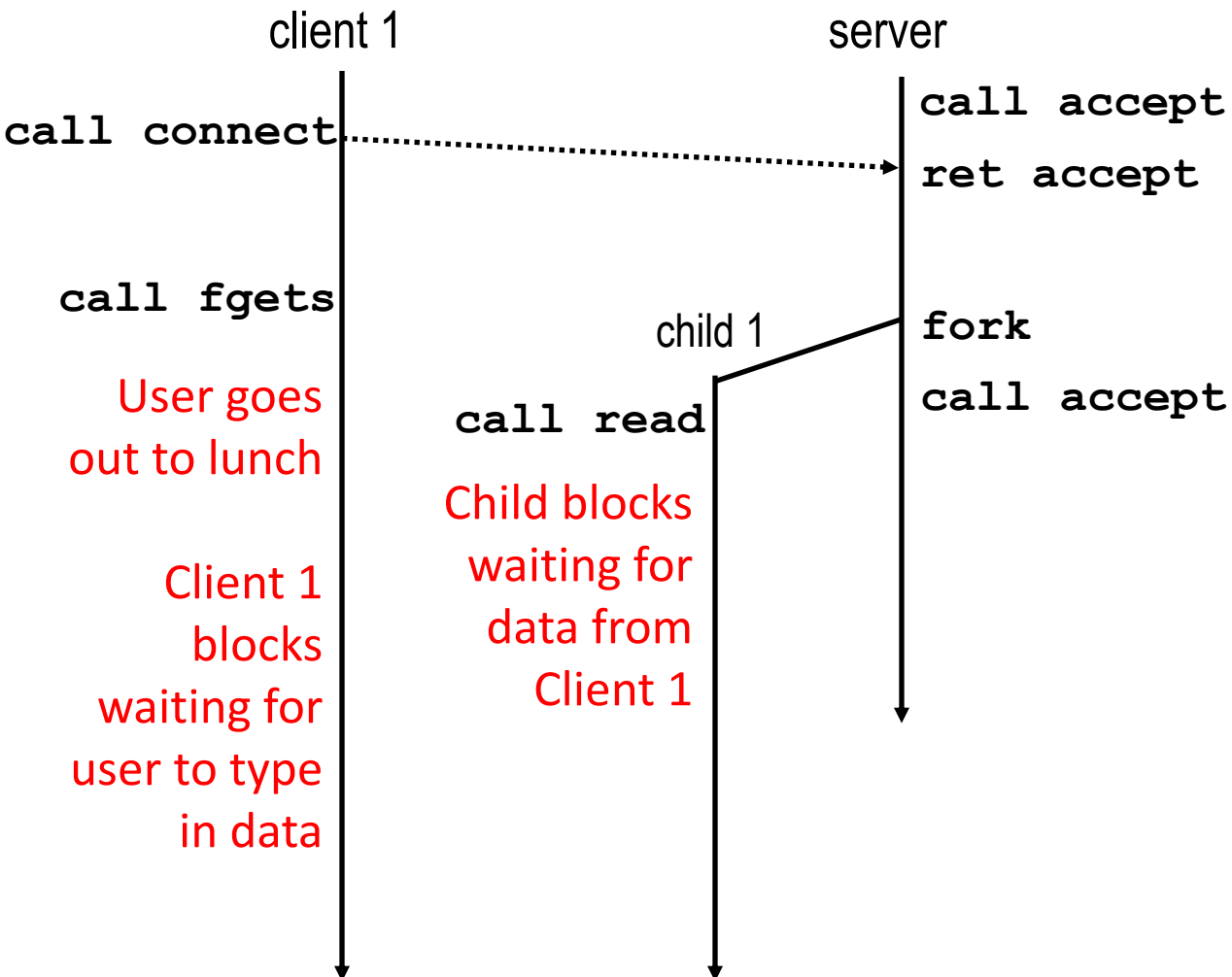
- Programmer manually interleaves multiple logical flows
- All flows share the same address space
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## 3. Thread-based

- Kernel automatically interleaves multiple logical flows
- Each flow shares the **same** address space
- Hybrid of of process-based and event-based

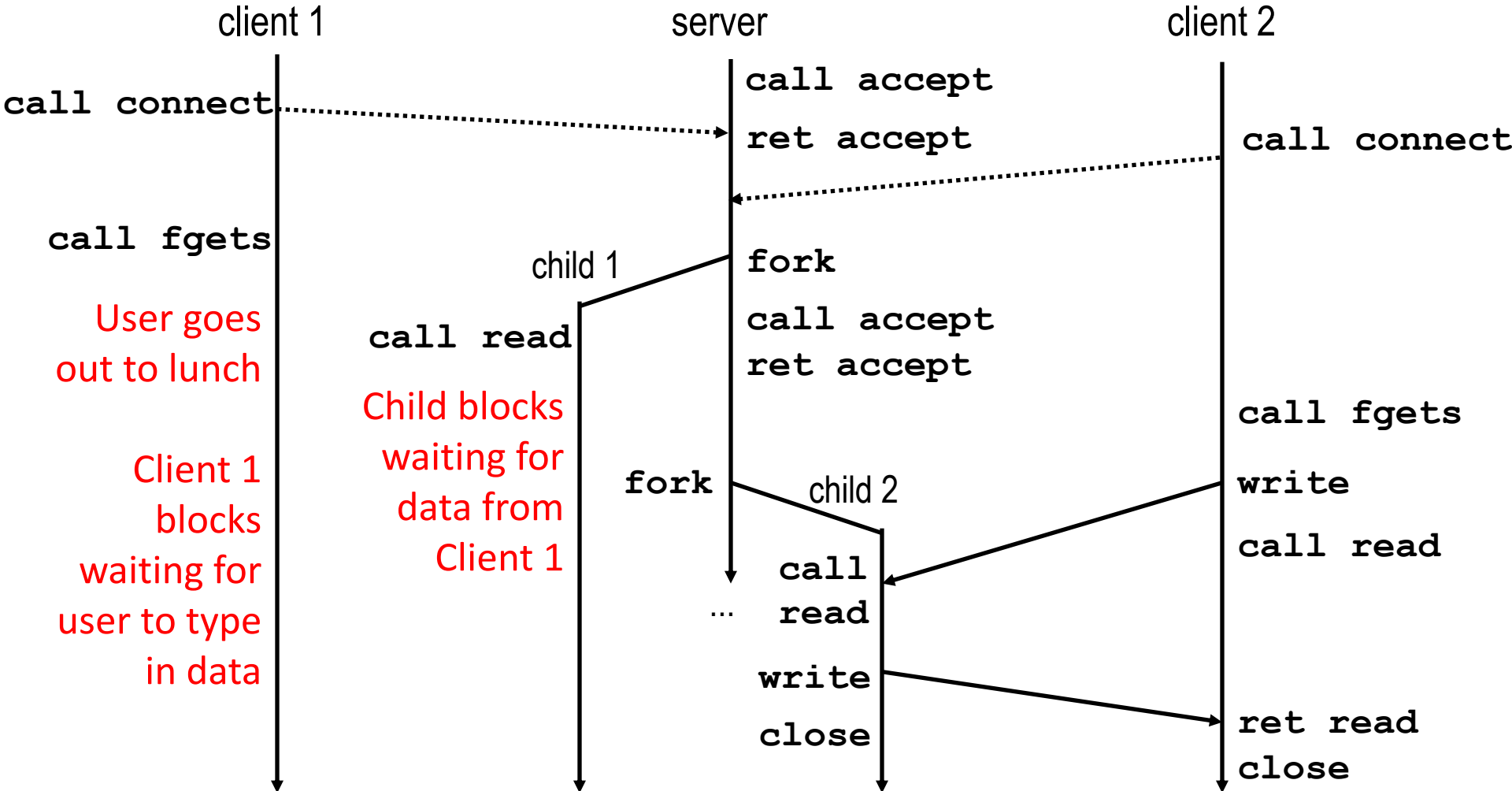
# Approach #1: Process-based Servers

- Spawn separate process for each client



# Approach #1: Process-based Servers

- Spawn separate process for each client



# 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

echoserverp.c

# Making a Concurrent 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);    /* Child services client */
        Close(connfd);  /* child closes connection with client */
        exit(0);
    }
}
```

echoserverp.c



# Making a Concurrent 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);
        if (Fork() == 0) {

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

echoserverp.c

# Making a Concurrent Echo Server

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

echoserverp.c

# Making a Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
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    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 */
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            exit(0);        /* Child exits */
        }
        Close(connfd); /* Parent closes connected socket (important!) */
    }
}
```

echoserverp.c

# Process-Based Concurrent Echo Server

```
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!) */
    }
}
```

echoserverp.c

# Process-Based Concurrent Echo Server (cont)

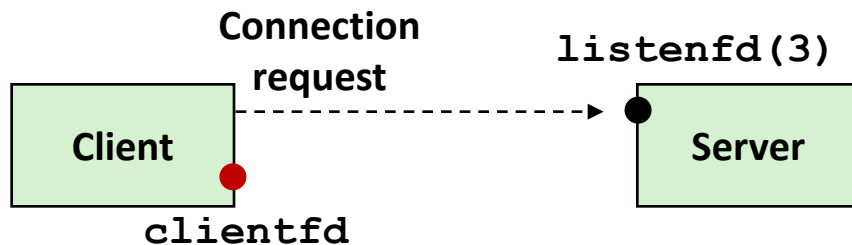
```
void sigchld_handler(int sig)
{
    while (waitpid(-1, 0, WNOHANG) > 0)
        ;
    return;
}
echoserverp.c
```

- Reap all zombie children

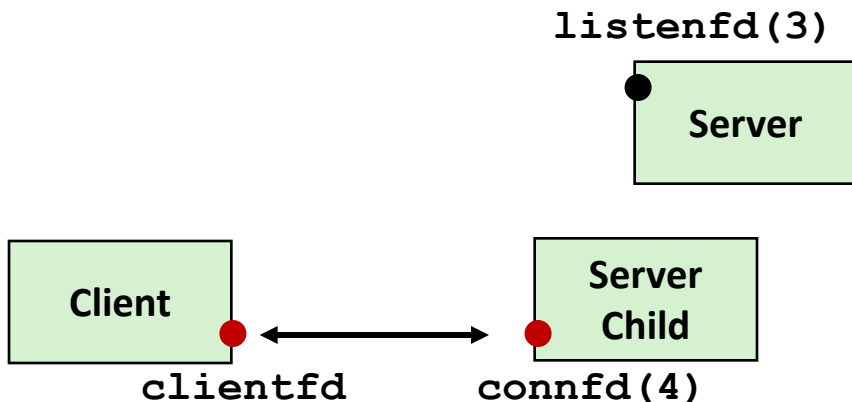
# Concurrent Server: `accept` Illustrated



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

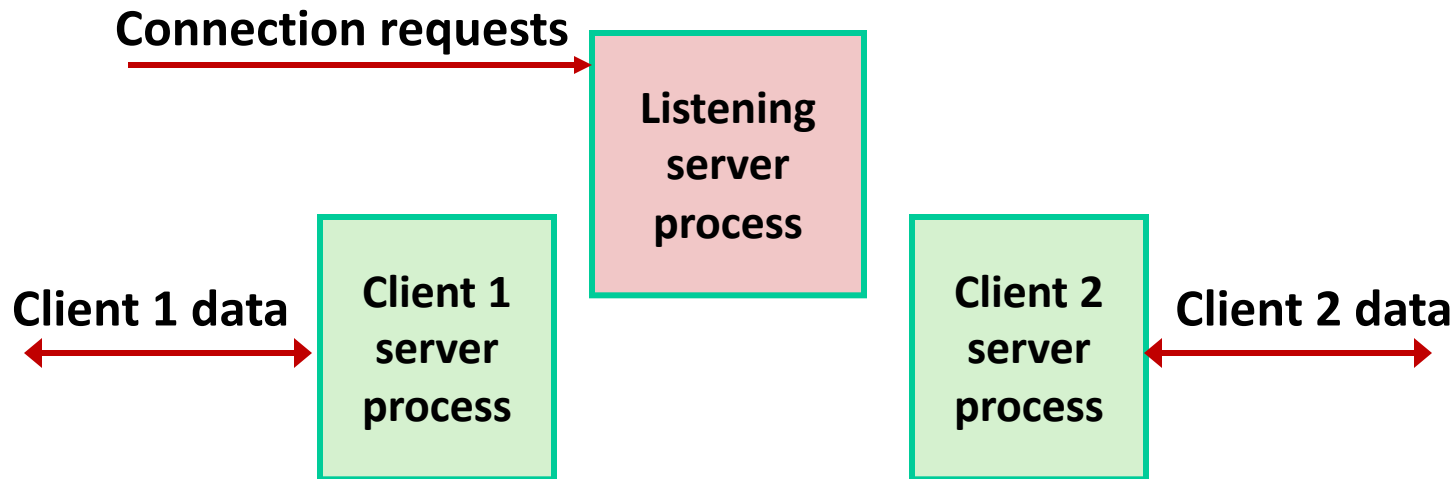


*2. Client makes connection request by calling `connect`*



*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`

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

    listenfd = Open_listenfd(1);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfd = Accept(listenfd, &clientaddr, &clientlen);
        if (Fork() == 0)
            echo(connfd); /* Child echoes client */
        Close(connfd); /* Parent closes connection with client */
        exit(0); /* Parent exits */
    }
}
```





# 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)

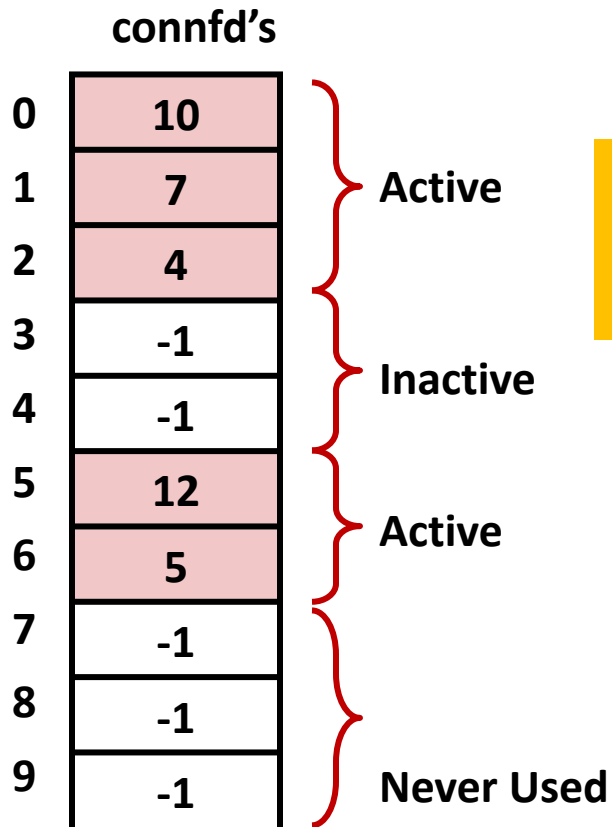
# Approach #2: Event-based Servers

- **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

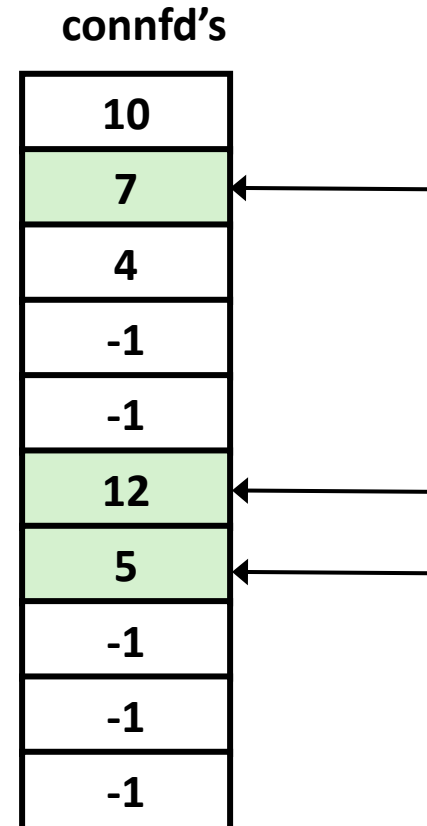
Active Descriptors

listenfd = 3



Anything happened?

Pending Inputs  
listenfd = 3



# 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

# Quiz

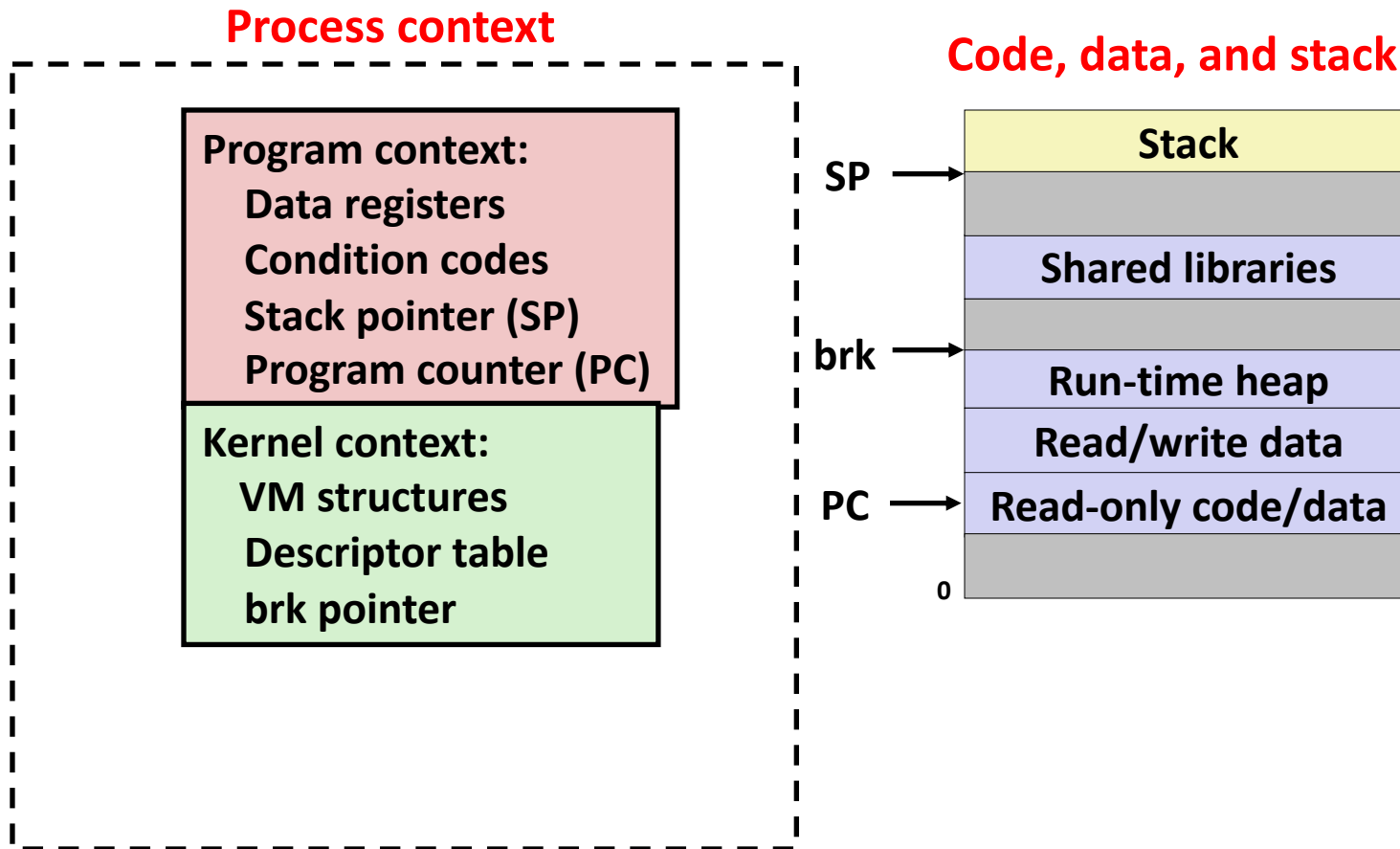
<https://canvas.cmu.edu/courses/28101/quizzes/77027>

# Approach #3: Thread-based Servers

- **Very similar to approach #1 (process-based)**
  - ...but using threads instead of processes

# Traditional View of a Process

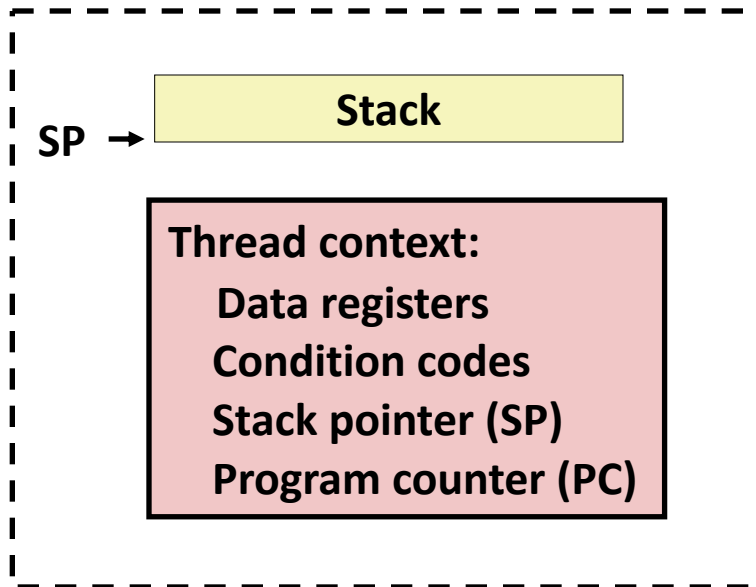
- Process = process context + code, data, and stack



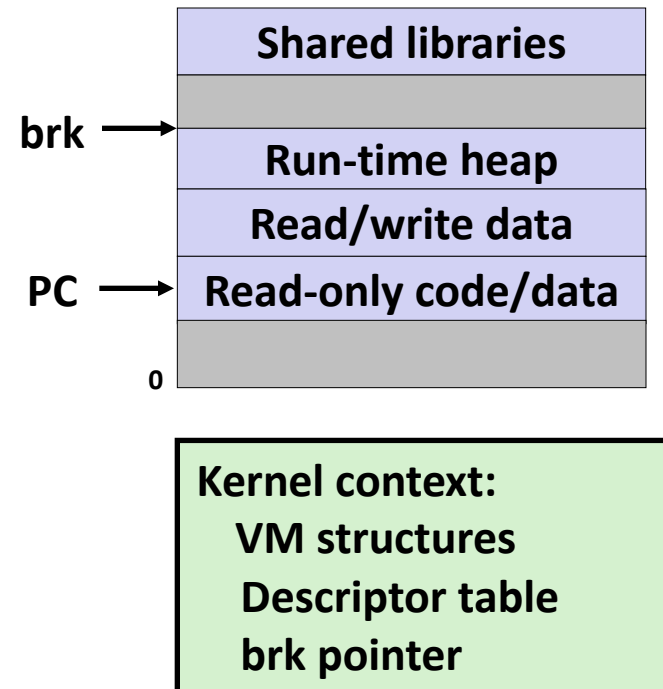
# Alternate View of a Process

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

## Thread (main thread)



## Code, data, and kernel context





# 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)**

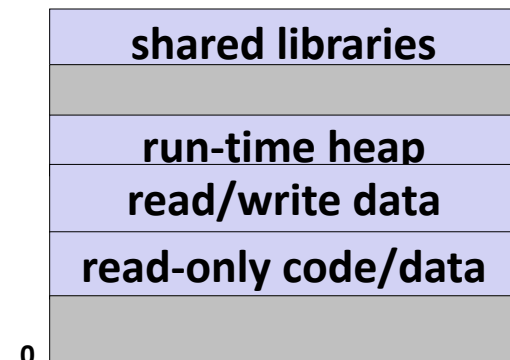
**stack 1**

**stack 2**

**Thread 1 context:**  
 Data registers  
 Condition codes  
 SP<sub>1</sub>  
 PC<sub>1</sub>

**Thread 2 context:**  
 Data registers  
 Condition codes  
 SP<sub>2</sub>  
 PC<sub>2</sub>

**Shared code and data**

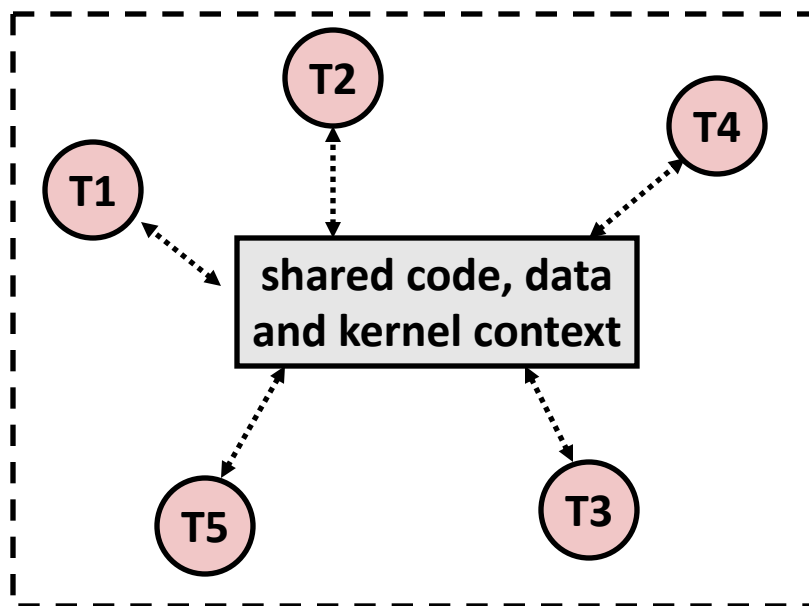


**Kernel context:**  
 VM structures  
 Descriptor table  
 brk pointer

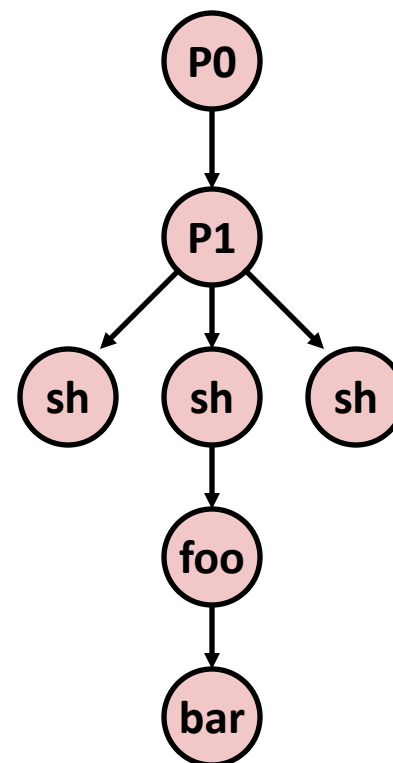
# Logical View of Threads

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

Threads associated with process foo



Process hierarchy



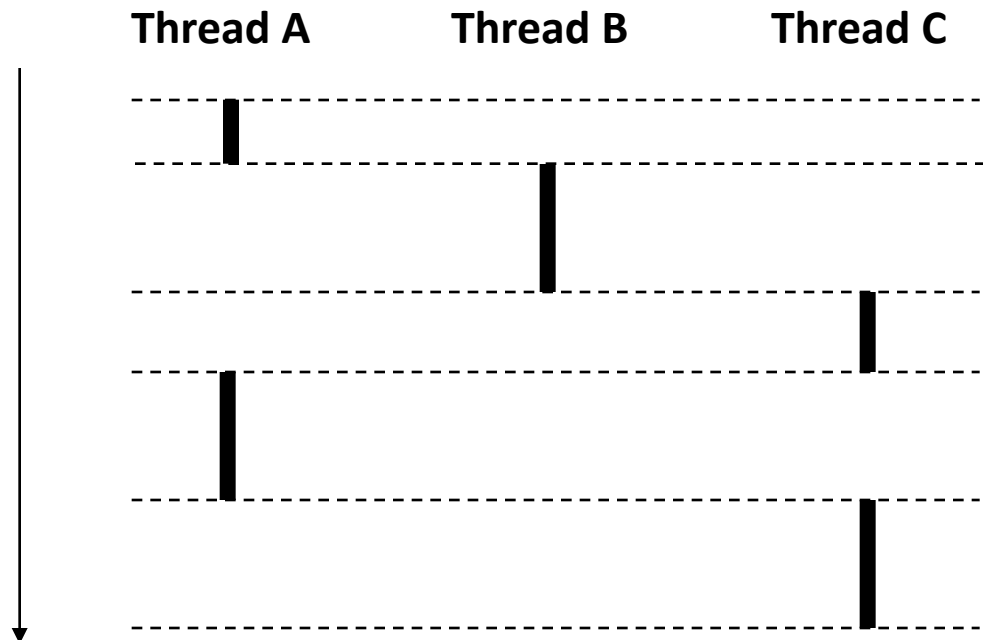
# Concurrent Threads

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

- **Examples:**

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

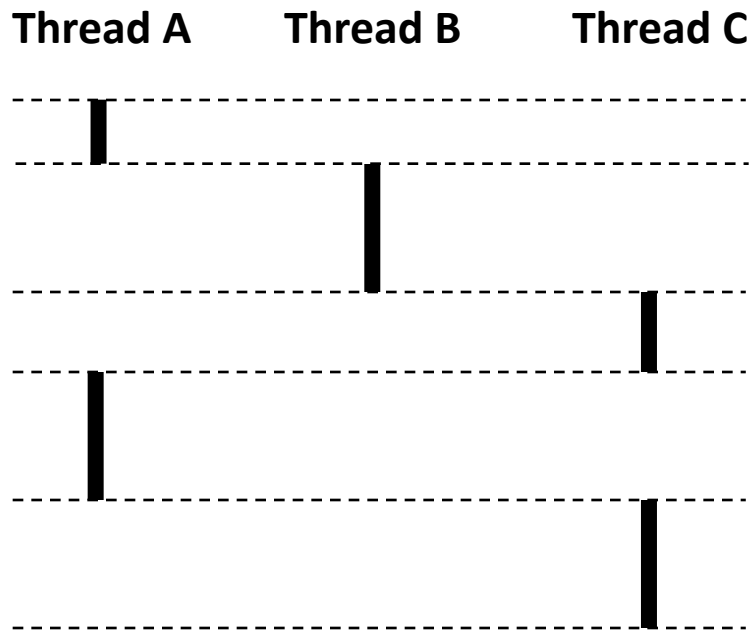
Time



# Concurrent Thread Execution

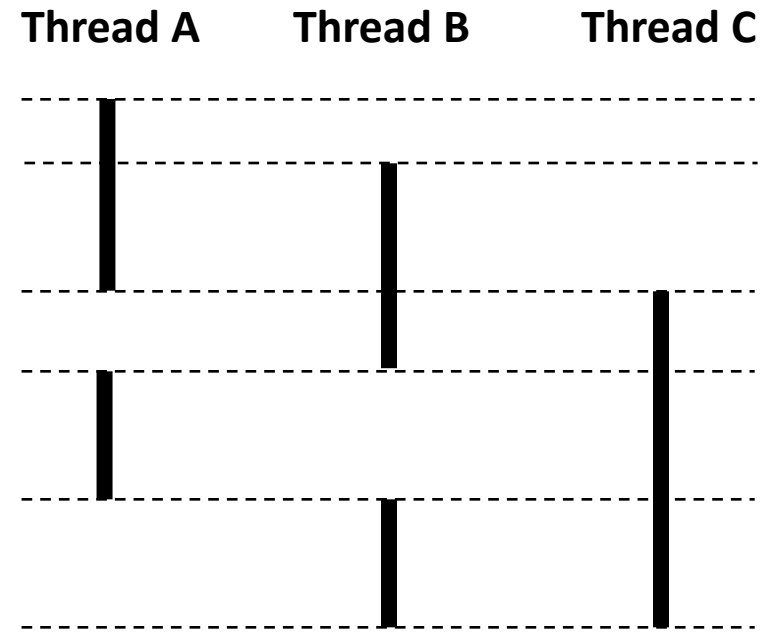
## ■ Single Core Processor

- Simulate parallelism by time slicing



## ■ Multi-Core Processor

- Can have true parallelism



Run 3 threads on 2 cores

# Threads vs. Processes

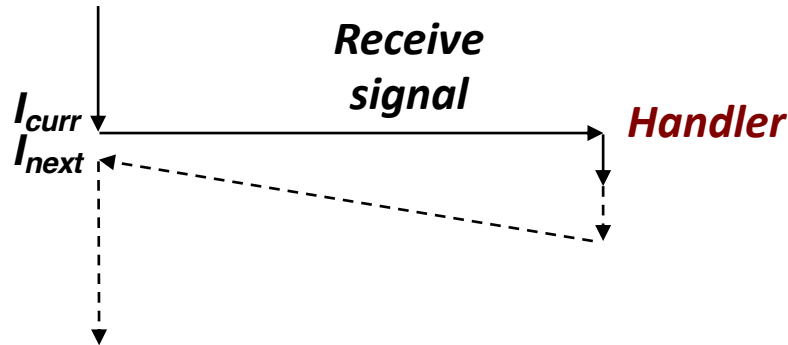
## ■ How threads and processes are similar

- 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

# Threads vs. Signals



- **Signal handler shares state with regular program**
  - Including stack
- **Signal handler interrupts normal program execution**
  - Unexpected procedure call
  - Returns to regular execution stream
  - *Not* a peer
- **Limited forms of synchronization**
  - Main program can block / unblock signals
  - Main program can pause for signal

# 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;
}

```

Thread ID

Thread attributes  
(usually NULL)

Thread routine

Thread arguments  
(void \*p)

hello.c

Return value  
(void \*\*p)

```

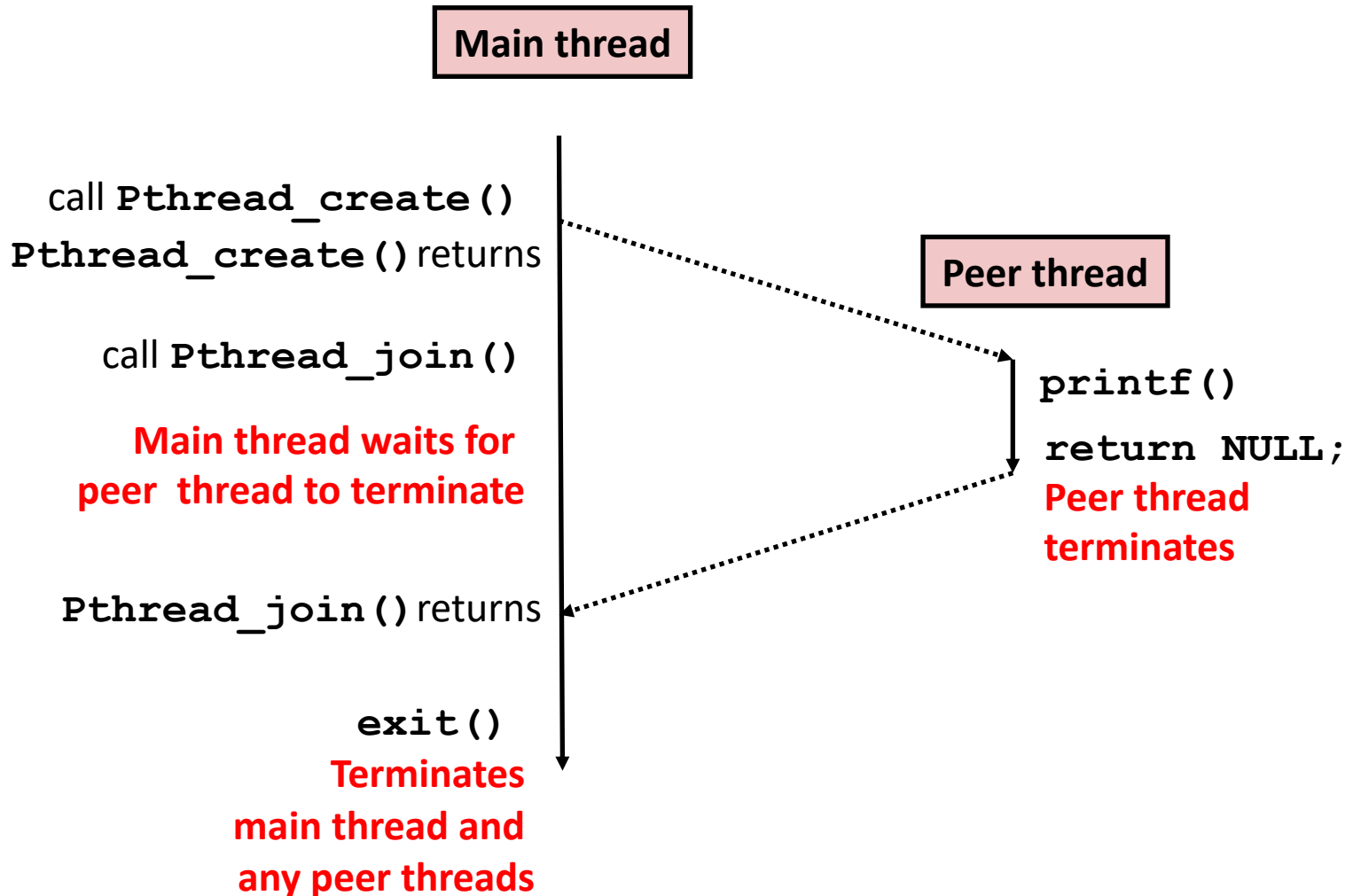
void *thread(void *vargp) /* thread routine */
{
    printf("Hello, world!\n");
    return NULL;
}

```

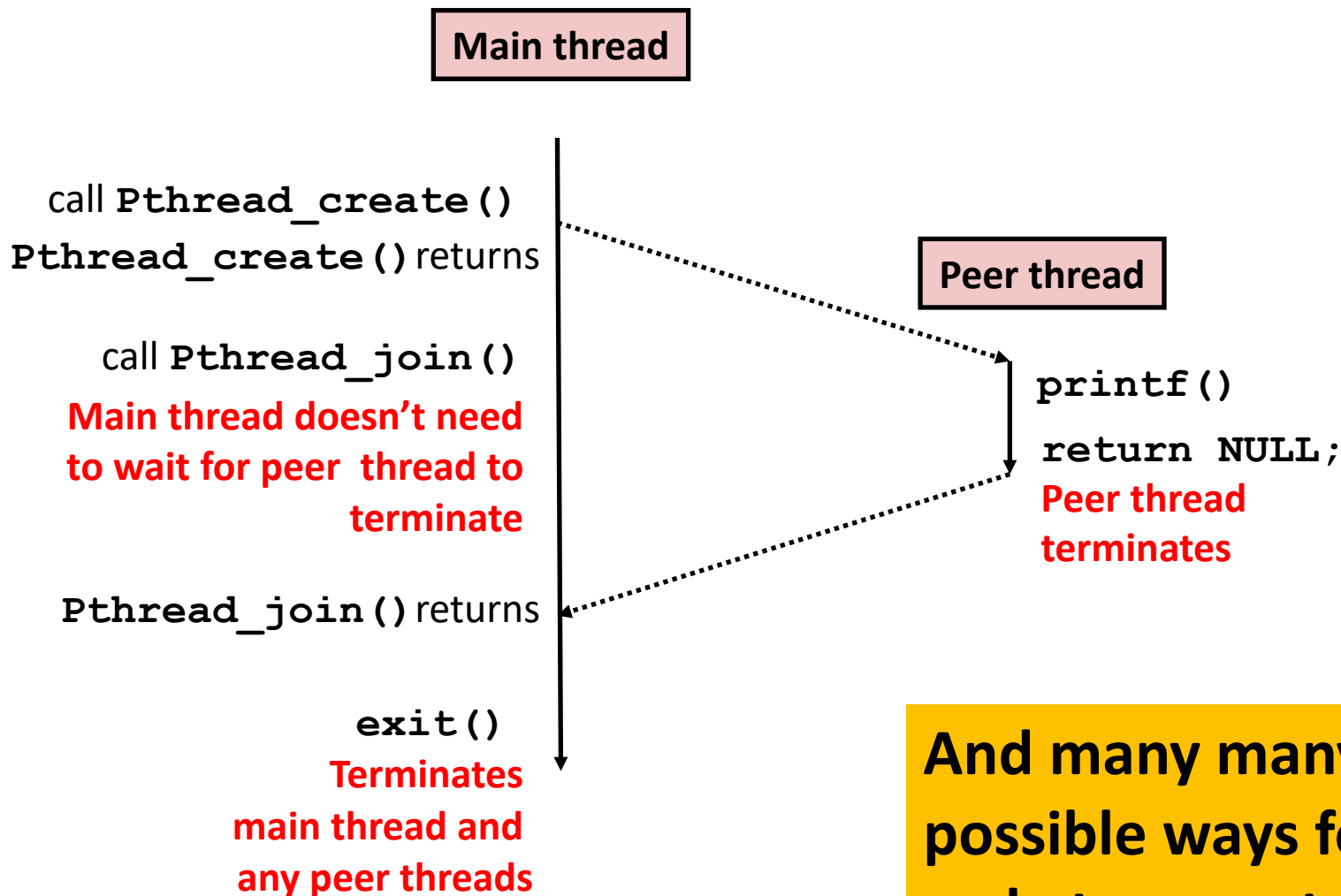
hello.c



# Execution of Threaded “hello, world”



# Or, ...



**And many many more possible ways for this code to execute.**

# Thread-Based Concurrent Echo Server

```
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;
}
```

echoserv.c

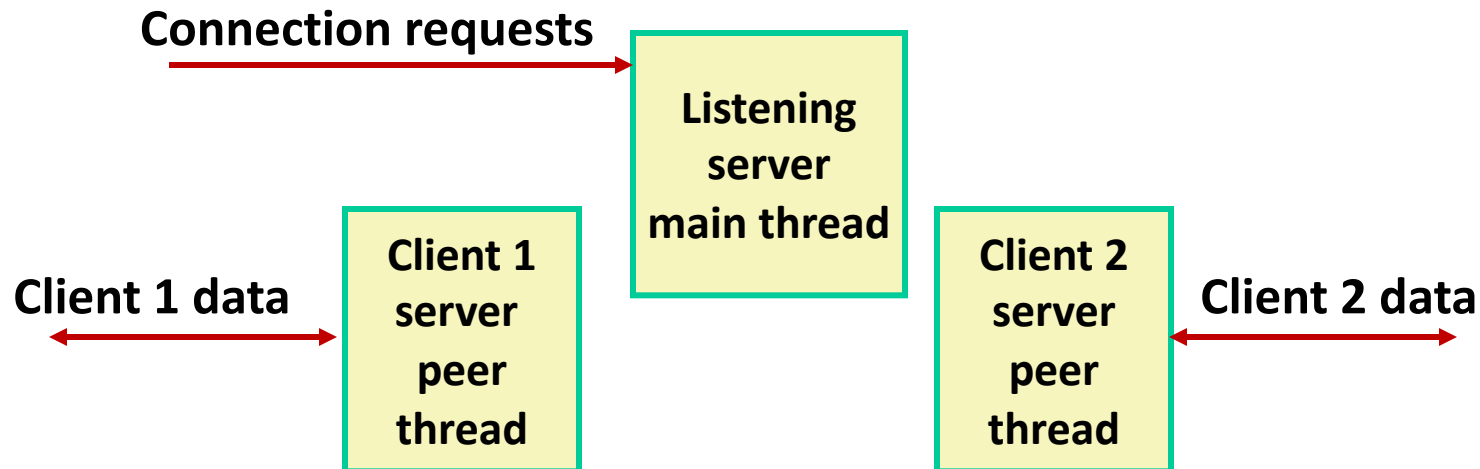
- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of **Malloc()** ! [but not **Free()**]

# 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;
}
echoserv.c
```

- 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



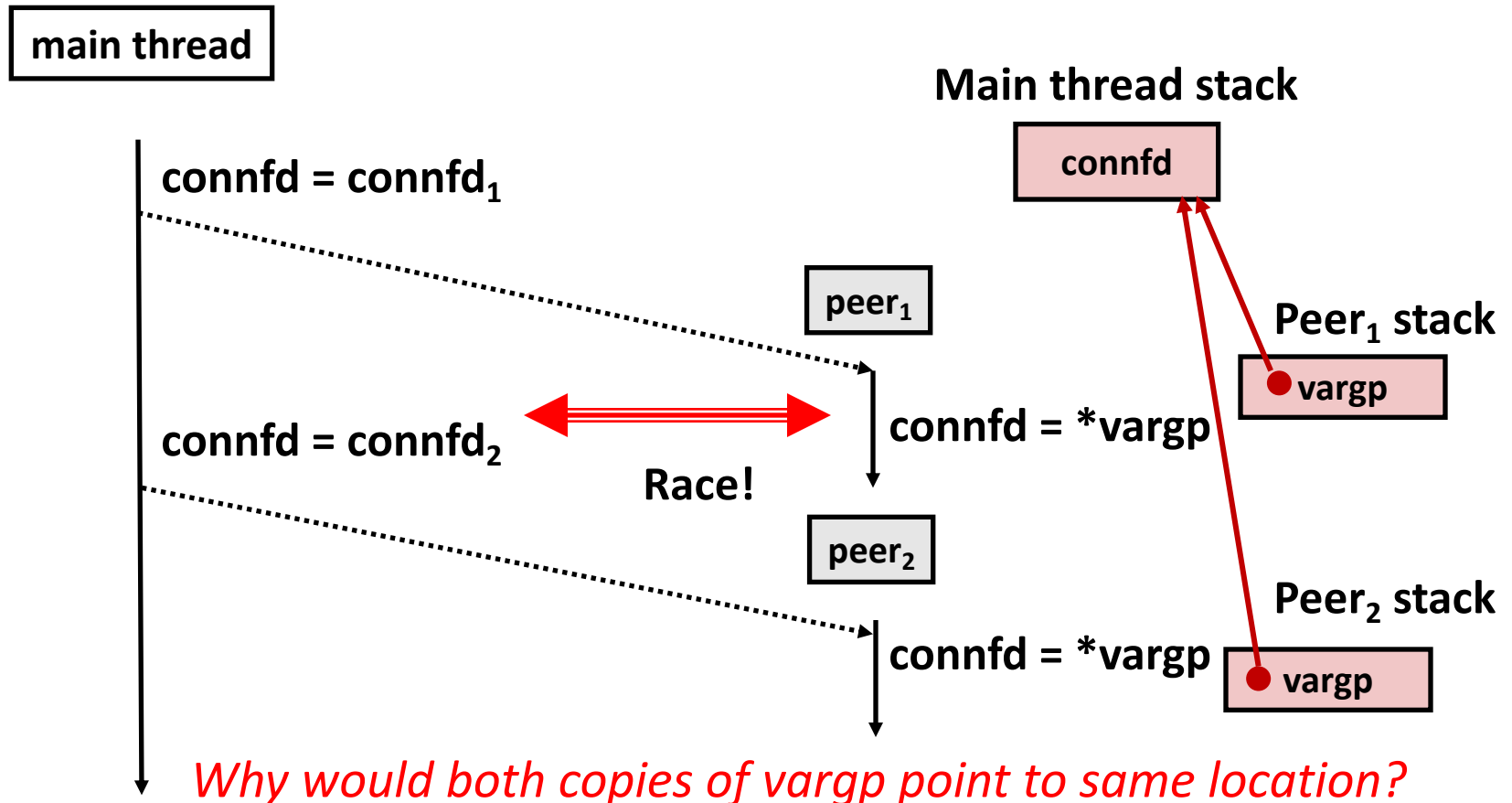
- Each client handled by individual peer thread
- Threads share all process state except TID
- Each thread has a separate stack for local variables

# 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)

# Potential Form of Unintended Sharing

```
while (1) {
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
    Pthread_create(&tid, NULL, thread, &connfd);
}
```



# 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)**

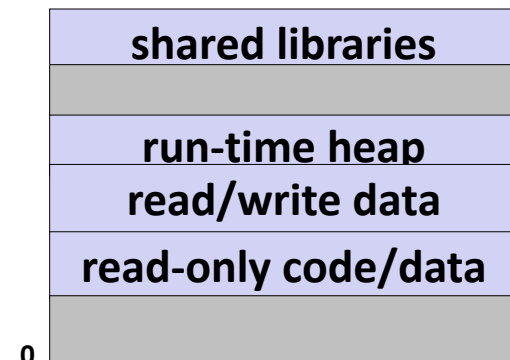
**stack 1**

**stack 2**

**Thread 1 context:**  
 Data registers  
 Condition codes  
 SP<sub>1</sub>  
 PC<sub>1</sub>

**Thread 2 context:**  
 Data registers  
 Condition codes  
 SP<sub>2</sub>  
 PC<sub>2</sub>

**Shared code and data**



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



# But ALL memory is shared

Thread 1 context:  
Data registers  
Condition codes  
 $SP_1$   
 $PC_1$

Thread 2 context:  
Data registers  
Condition codes  
 $SP_2$   
 $PC_2$

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

stack 1

stack 2

shared libraries

run-time heap

read/write data

read-only code/data

0

Kernel context:  
VM structures  
Descriptor table  
brk pointer

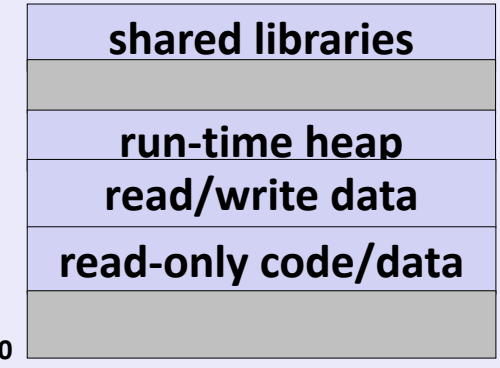
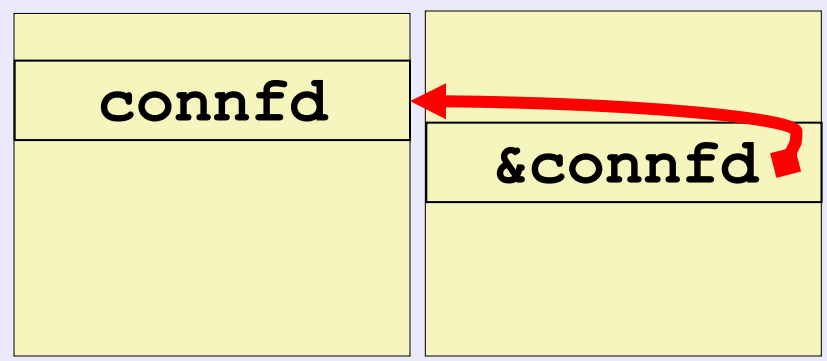
```
while (1) {  
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);  
    Pthread_create(&tid, NULL, thread, &connfd);  
}
```

Thread 1 context:  
Data registers  
Condition codes  
SP<sub>1</sub>  
PC<sub>1</sub>

Thread 2 context:  
Data registers  
Condition codes  
SP<sub>2</sub>  
PC<sub>2</sub>

### Thread 1

### Thread 2



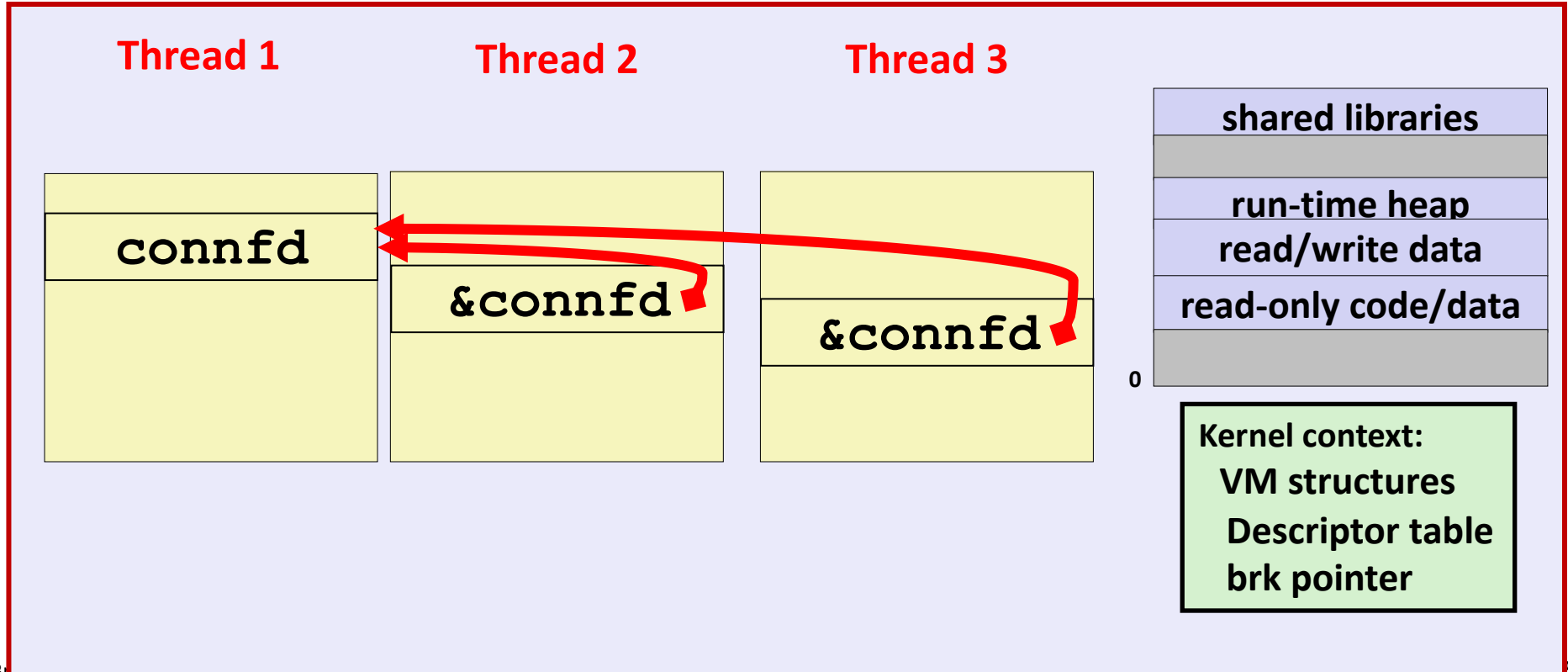
Kernel context:  
VM structures  
Descriptor table  
brk pointer

```
while (1) {  
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);  
    Pthread_create(&tid, NULL, thread, &connfd);  
}
```

Thread 1 context:  
Data registers  
Condition codes  
SP<sub>1</sub>  
PC<sub>1</sub>

Thread 2 context:  
Data registers  
Condition codes  
SP<sub>2</sub>  
PC<sub>2</sub>

Thread 3 context:  
Data registers  
Condition codes  
SP<sub>2</sub>  
PC<sub>2</sub>



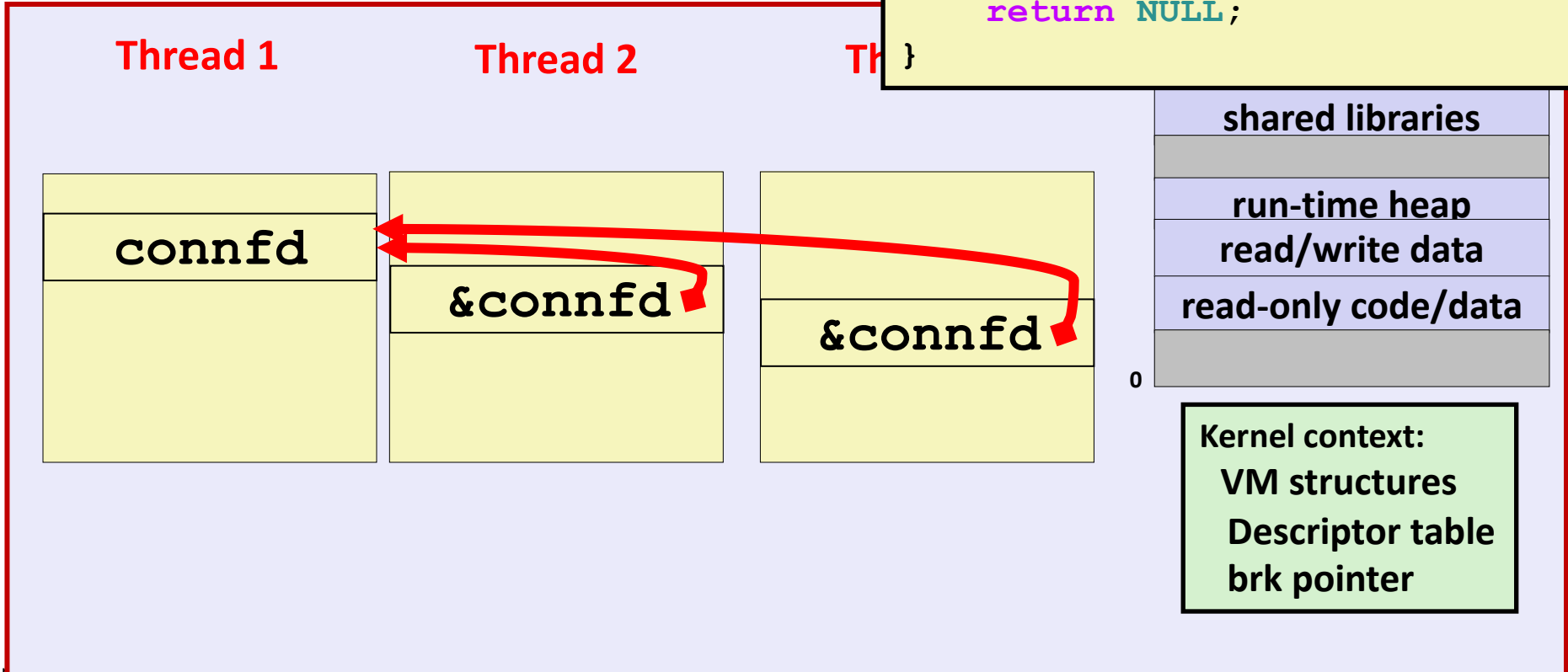
Thread 1 context:  
 Data registers  
 Condition codes  
 SP<sub>1</sub>  
 PC<sub>1</sub>

Thread 2 context:  
 Data registers  
 Condition codes  
 SP<sub>2</sub>  
 PC<sub>2</sub>

Thread  
 Data  
 Con  
 SP<sub>2</sub>  
 PC<sub>2</sub>

```

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



# Could this race occur?

## Main

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

## Thread

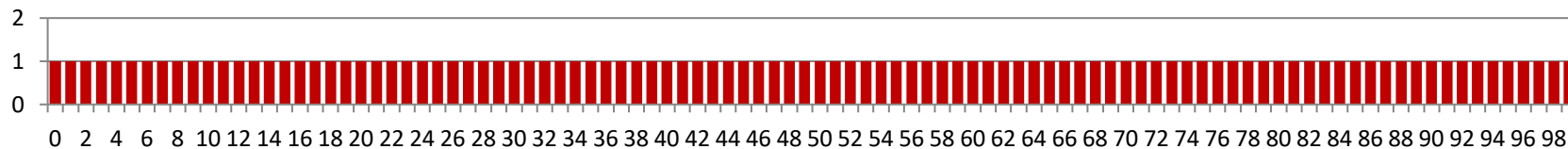
```
void *thread(void *vargp)
{
    int i = *((int *)vargp);
    Pthread_detach(pthread_self());
    save_value(i);
    return NULL;
}
```

## ■ Race Test

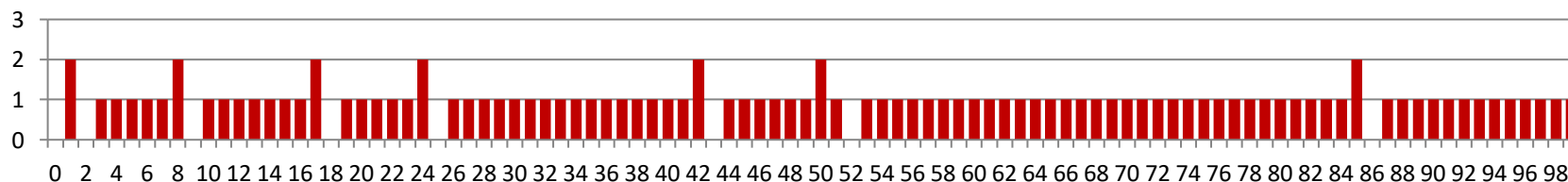
- If no race, then each thread would get different value of **i**
- Set of saved values would consist of one copy each of 0 through 99

# Experimental Results

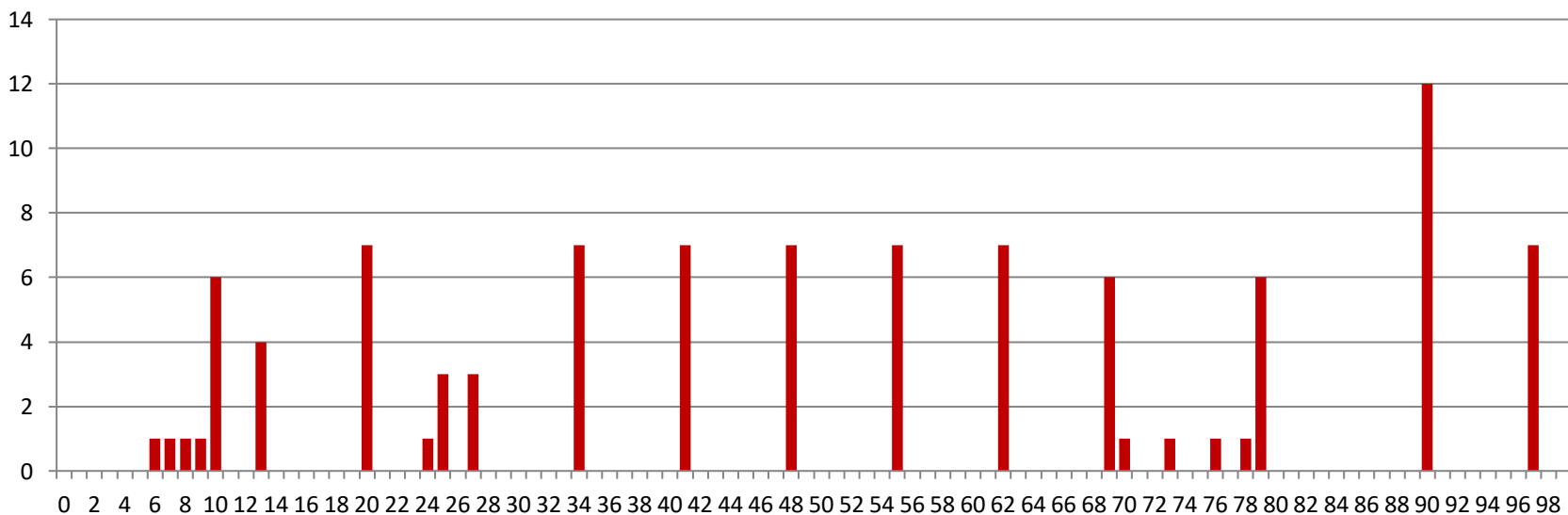
## No Race



## Single core laptop



## Multicore server



■ **The race can really happen!**

# Correct passing of thread arguments

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

```
/* 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