

Concurrent Programming

15-213/15-503: Introduction to Computer Systems
23rd Lecture, July 22, 2025

Instructors:

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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

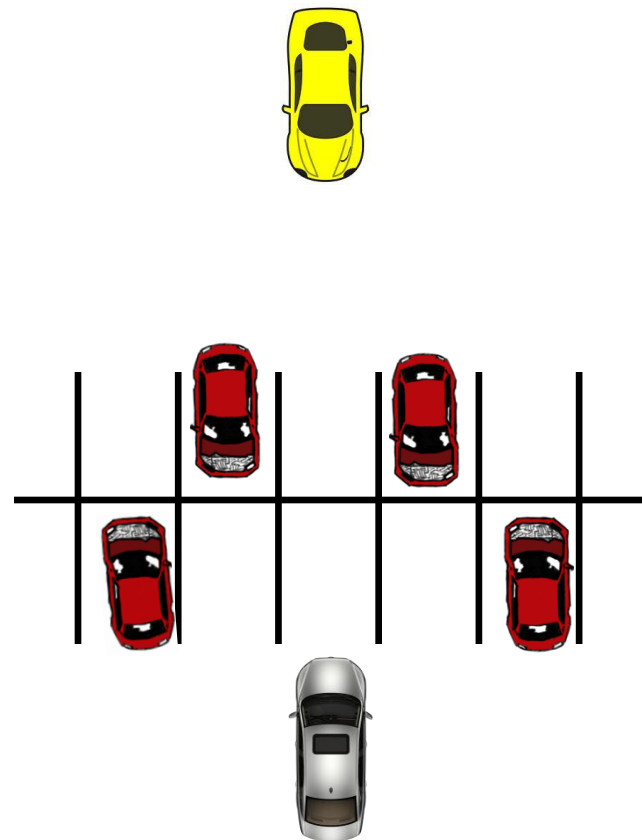
Concurrent Programming is Hard!

- **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

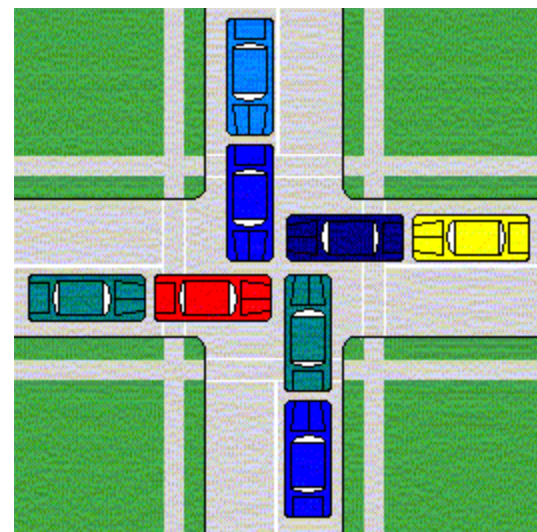
Data Race



```
/* Global shared variable */  
volatile long cnt = 0; /* Counter */  
void *thread(void *vargp)  
{  
    long i, niters =  
        *((long *)vargp);  
  
    for (i = 0; i < niters; i++)  
        cnt++;  
  
    return NULL;  
}
```



Deadlock



Deadlock

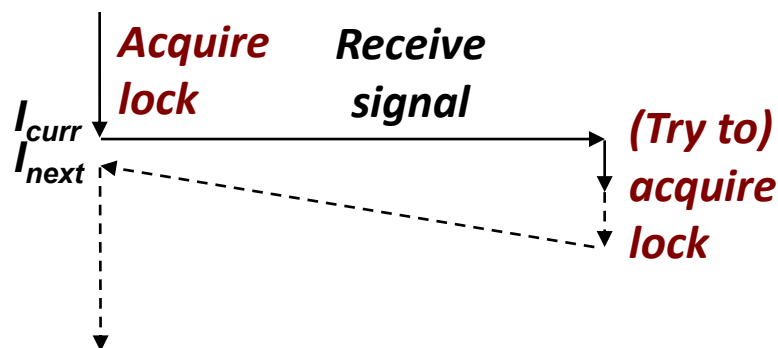
- Example from signal handlers.
- Why don't we use printf in handlers?



```
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

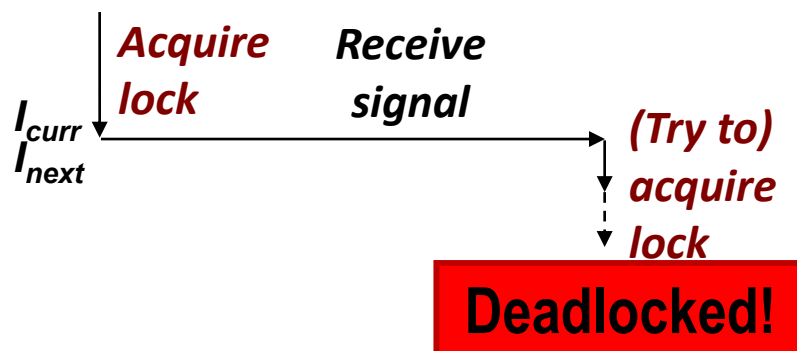
- Example from signal handlers.
- Why don't we use printf in handlers?



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    while (waitpid(-1, NULL, WNOHANG) > 0) continue; // reap all children
}
```

- **Printf code:**

- Acquire lock
- Do something
- Release lock



- What if signal handler interrupts call to printf?

Testing Printf Deadlock

```
static void sigchld(int unused) {
    int status;
    pid_t pid;
    while ((pid = waitpid(-1, &status, WNOHANG)) > 0) {
        printf("Child %d exited with status %04x\n", pid, status);
    }
}

int main(void) {
    signal(SIGCHLD, sigchld);
    for (int i = 0; i < 1000000; i++) {
        pid_t pid = fork();
        if (pid == 0)
            _exit(0);
        // in parent
        printf("Child #%d=%d started\n",
              i, pid);
    }
    return 0;
}
```


Testing Printf Deadlock

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static void sigchld(int unused) {
    int status;
    pid_t pid;
    while ((pid = waitpid(-1, &status, WNOHANG)) > 0) {
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        pid_t pid = fork();
        if (pid == 0)
            _exit(0);
        // in parent
        printf("Child #%d=%d started\n", i, pid);
    }
    return 0;
}
```

```
Child #0=1234 started
Child #1=1235 started
Child #2=1236 started
Child #3=1237 started
Child 1234 exited with status 0000
Child #4=1238 started
Child 1235 exited with status 0000
Child 1236 exited with status 0000
.
.
.
Child #3566=16979 started
and then, silence
```

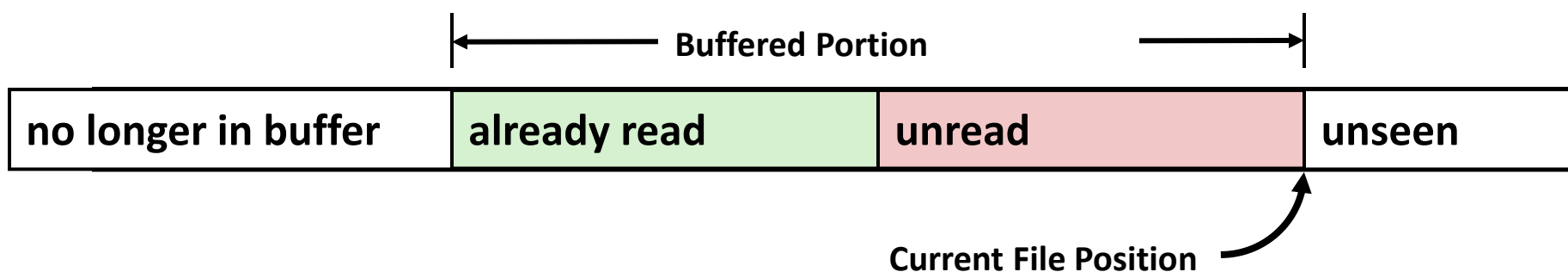
Testing Printf Deadlock

```
static void sigchld(int unused) {
    int status;
    pid_t pid;
    while ((pid = waitpid(-1, &status, WNOHANG)) > 0) {
        printf("Child %d exited with status %04x\n", pid, status);
    }
}
```

```
int main(void) {
    (gdb) bt
#0  0x00007ffff7b197fc in __lll_lock_wait_private ()
#1  0x00007ffff7a5b00e in _L_lock_1177 ()
#2  0x00007ffff7a557f4 in _IO_vfprintf_internal ()
#3  0x00007ffff7a604e9 in printf (
    format="Child %d exited with status %04x\n")
#4  0x0000000000400678 in sigchld ()
#5  <signal handler called>
#6  0x00007ffff7a5583f in _IO_vfprintf_internal ()
#7  0x00007ffff7a604e9 in printf (
    format="Child #%d=%d started\n")
#8  0x00000000004006d2 in main ()
}
```

Why Does Printf require Locks?

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

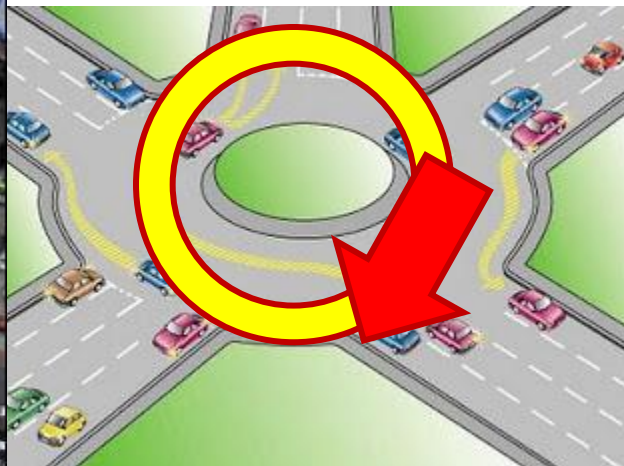


- Require locks to access the shared buffers

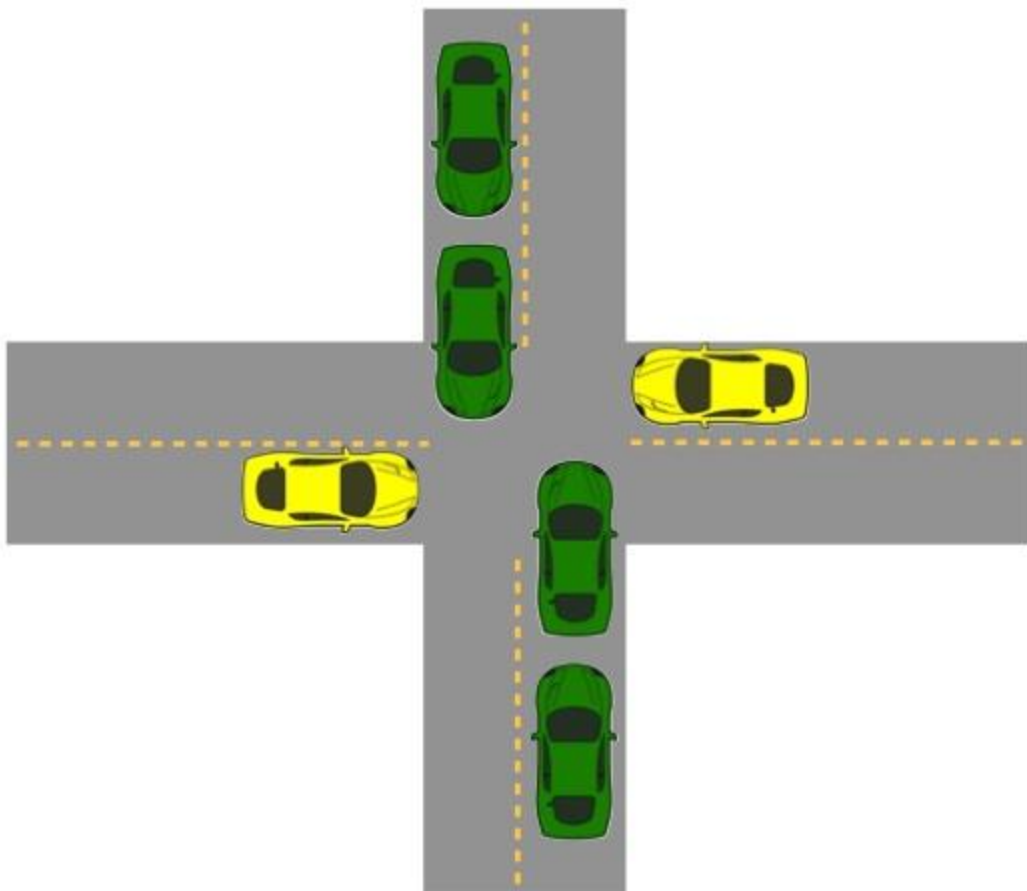
Livelock



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!

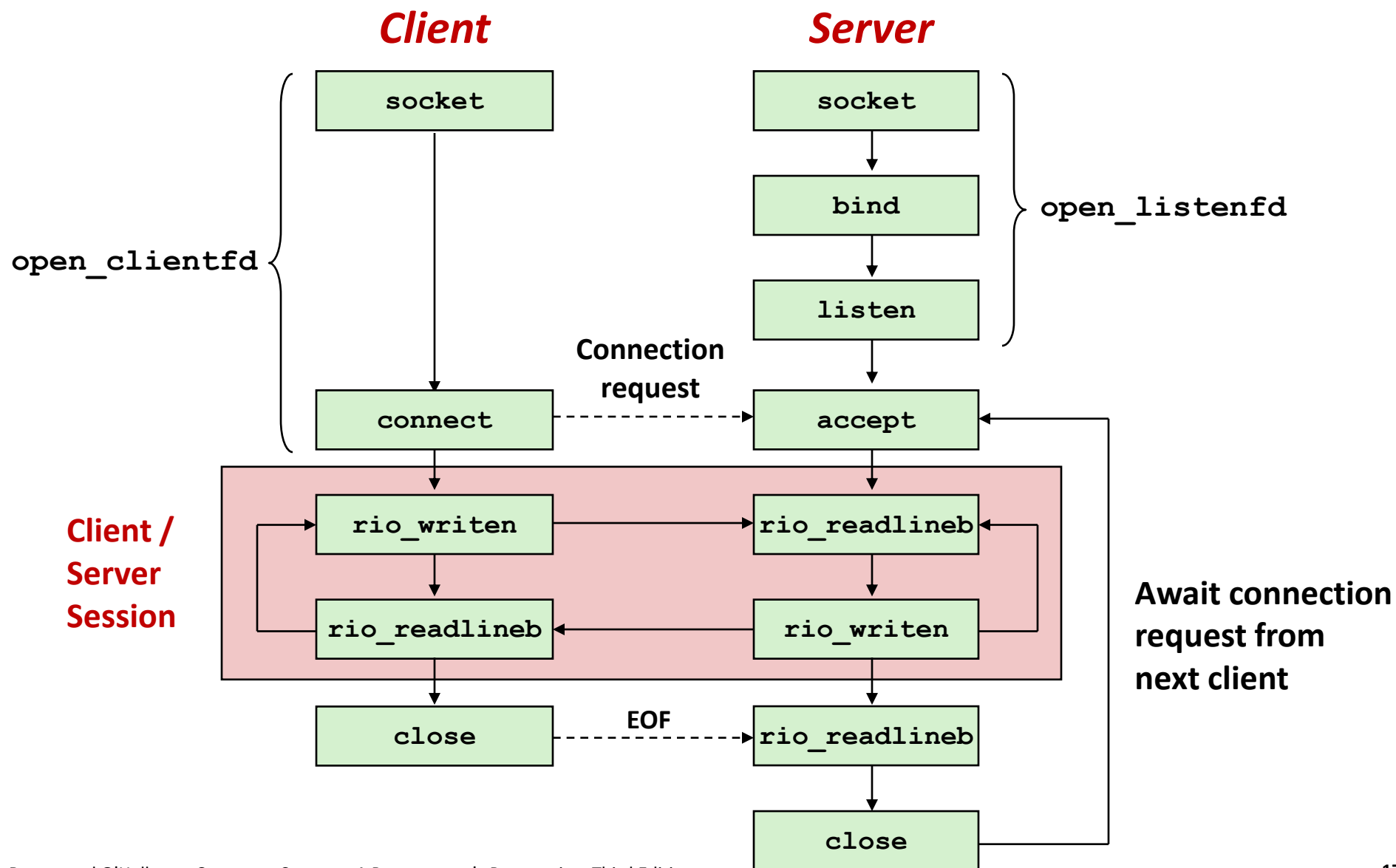
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 - ***Livelock / Starvation / Fairness***: external events and/or system scheduling decisions can prevent sub-task progress
 - Example: people always jump in front of you in line
- **Many aspects of concurrent programming are beyond the scope of our 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 ...

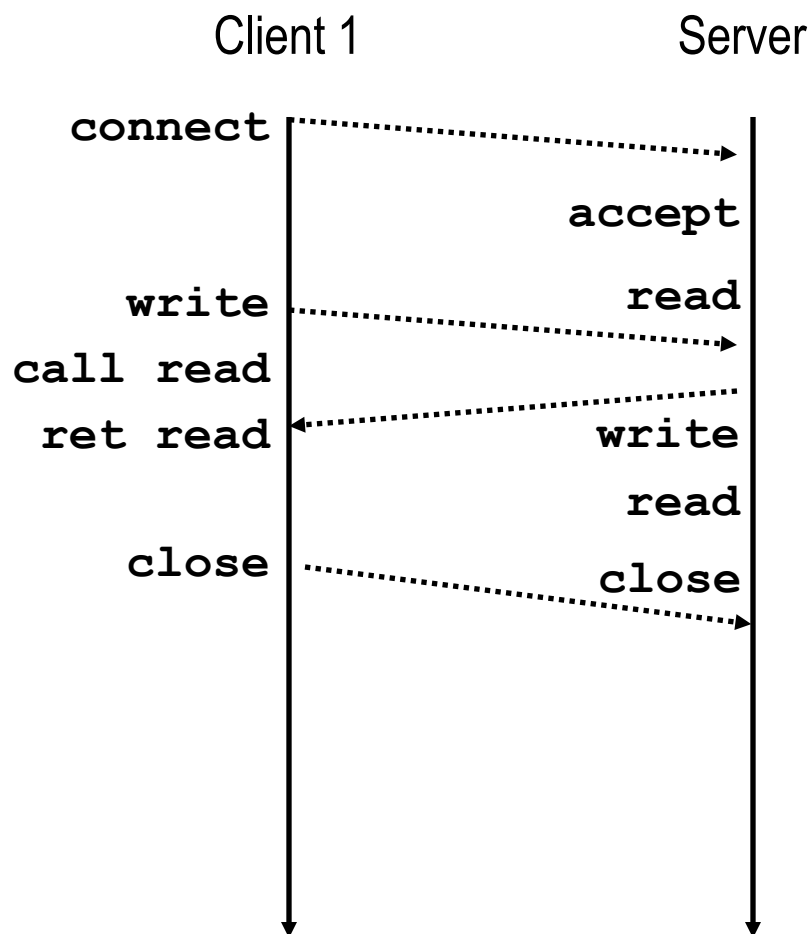
it can be useful and **more and more** necessary!

Reminder: Iterative Echo Server



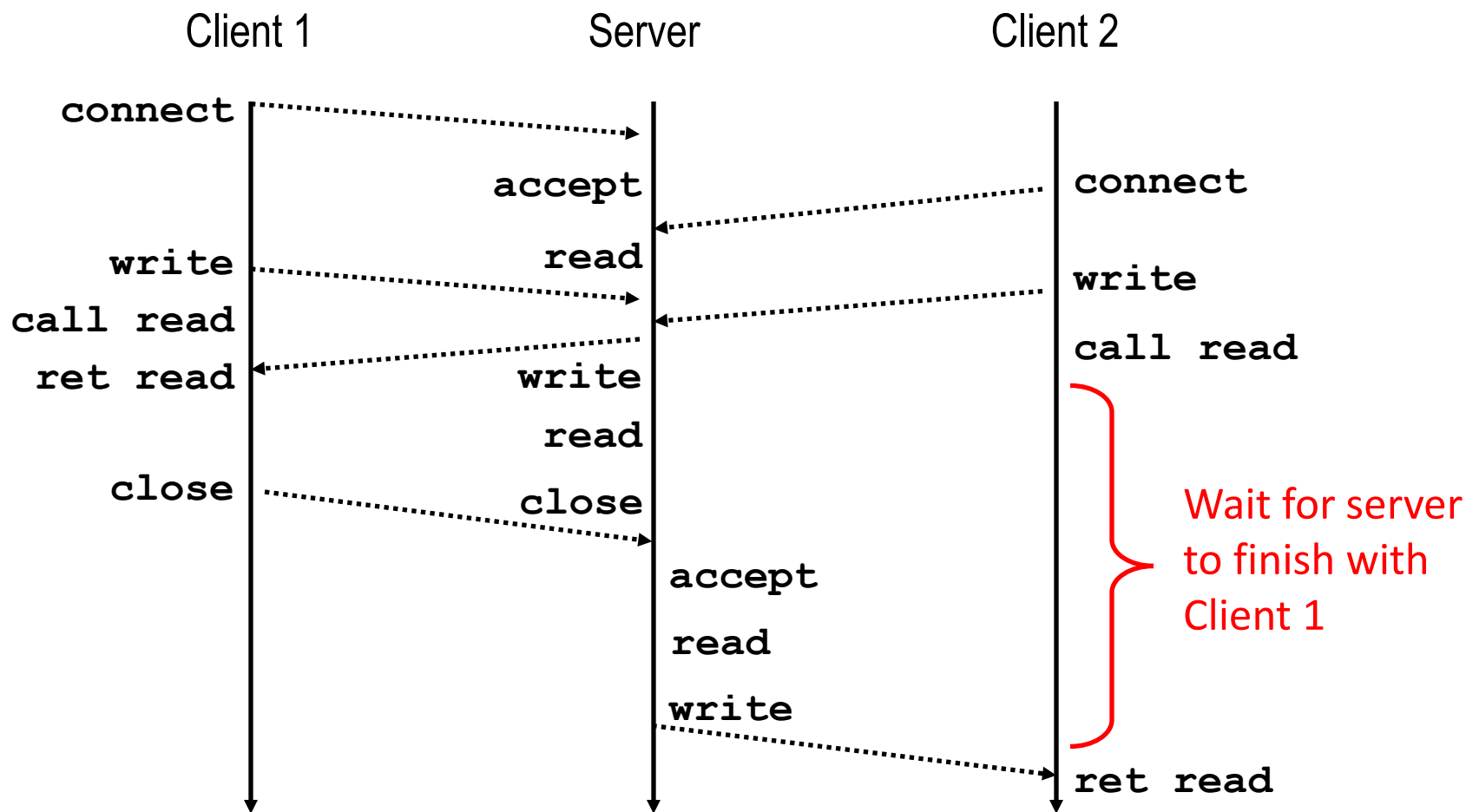
Iterative Servers

- Iterative servers process one request at a time



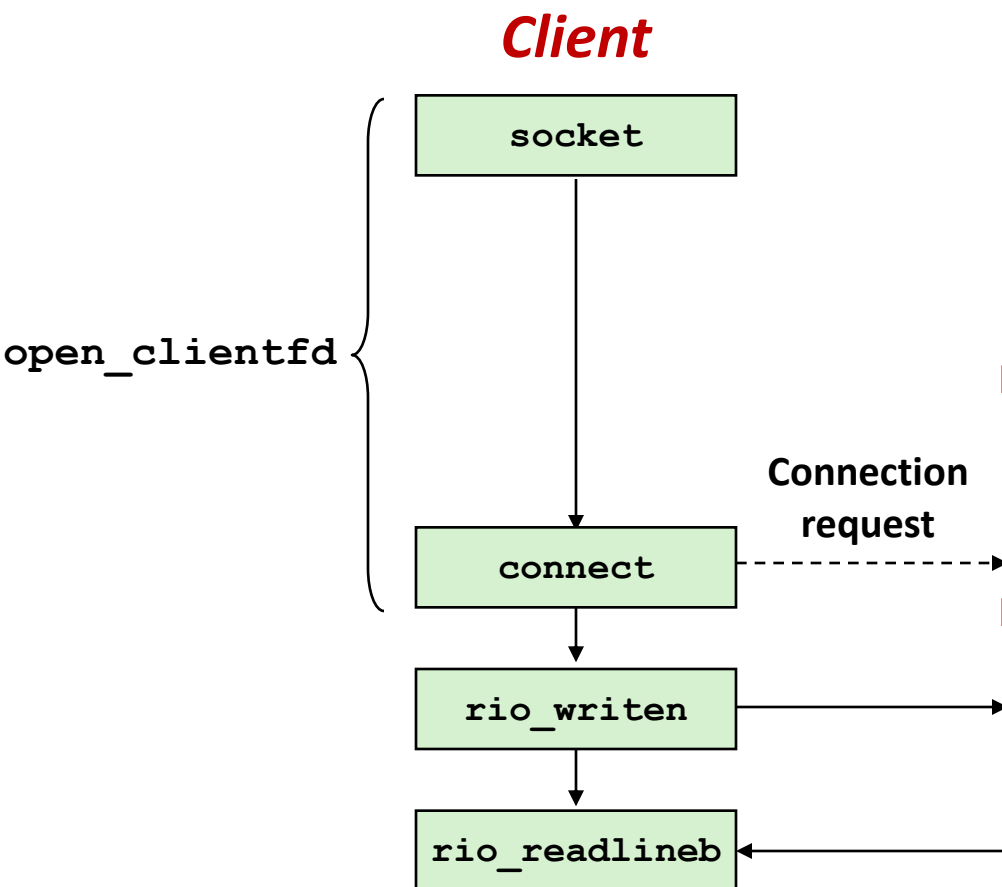
Iterative Servers

- 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”

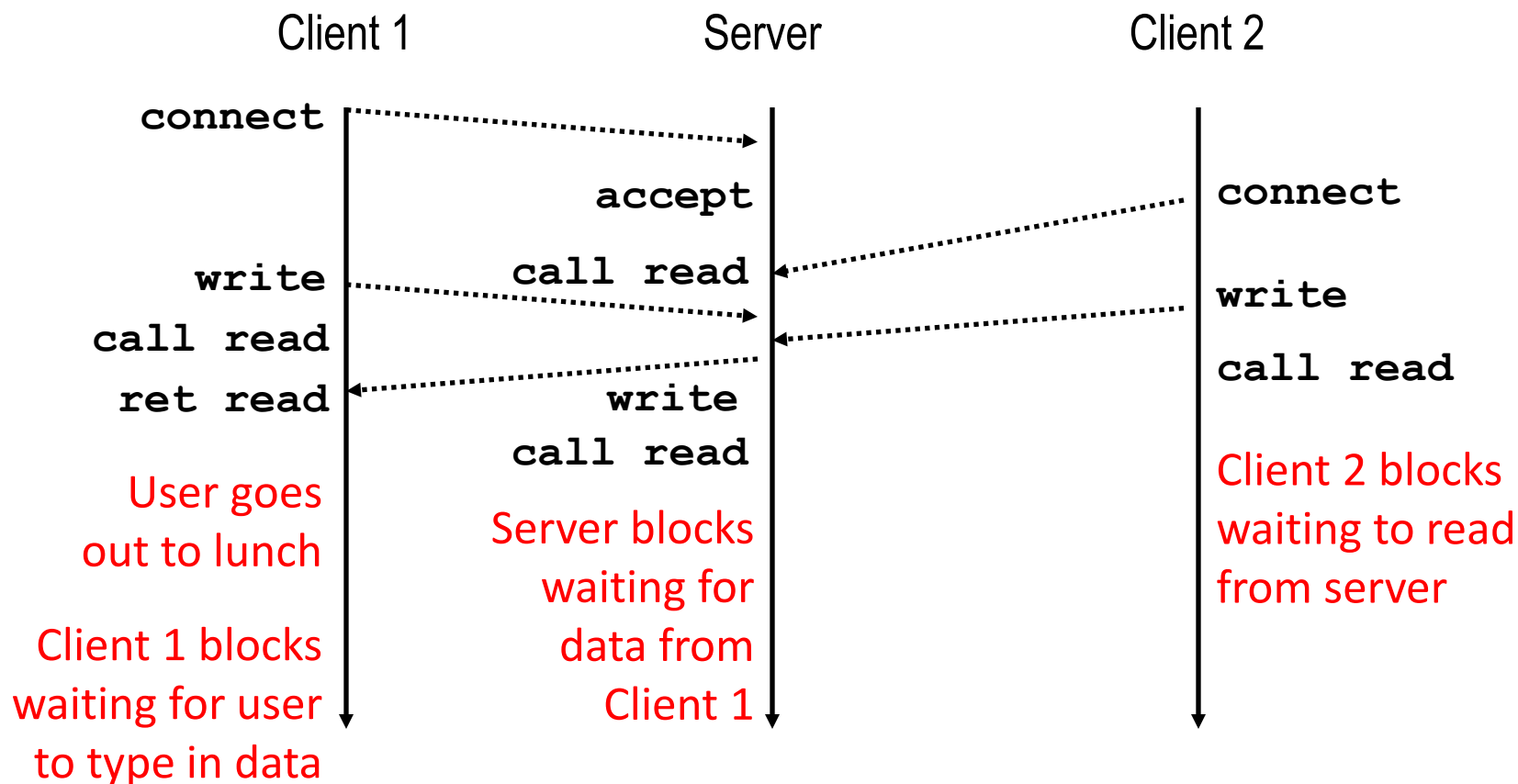
- Call to rio_writen returns

- 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

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2. Event-based

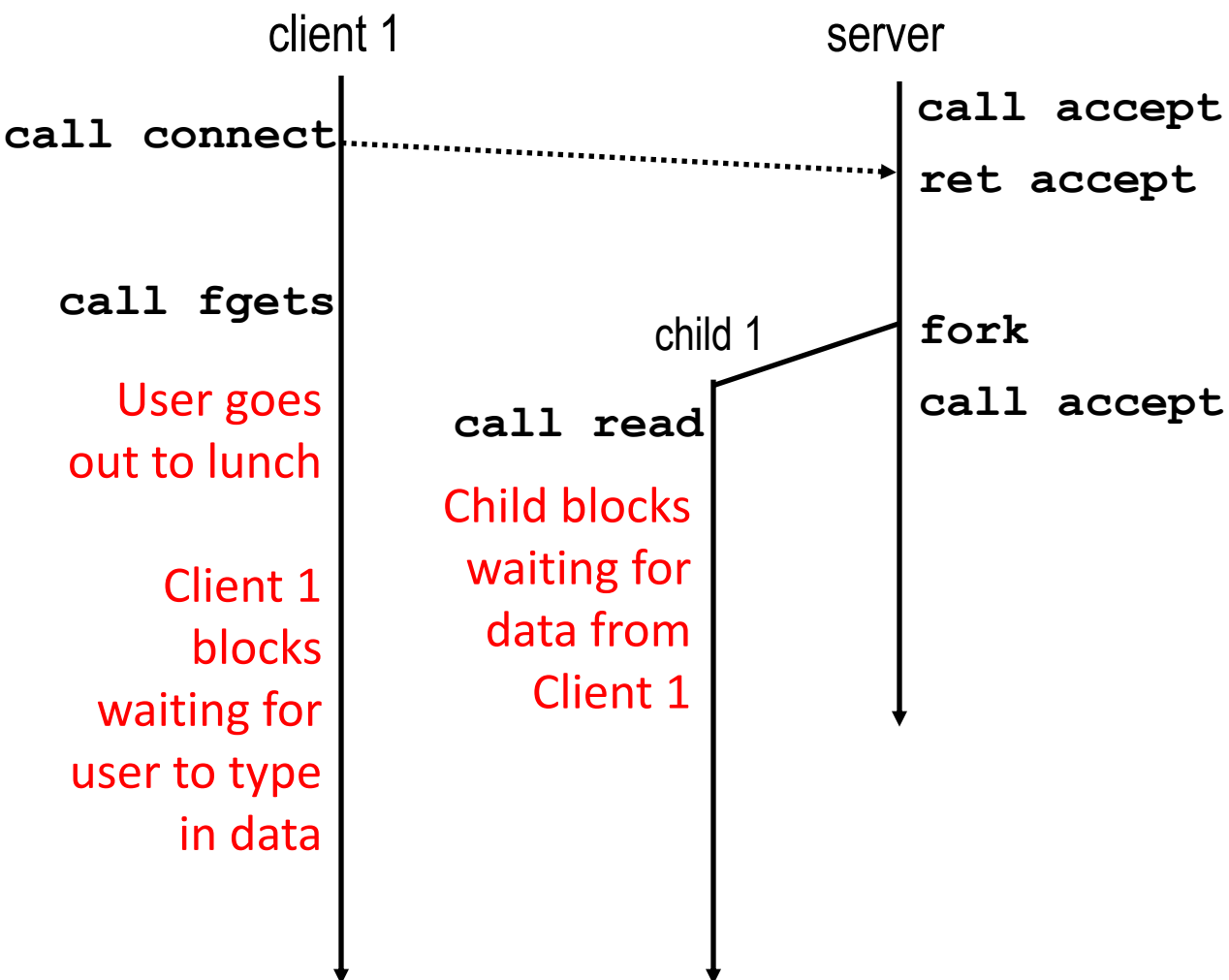
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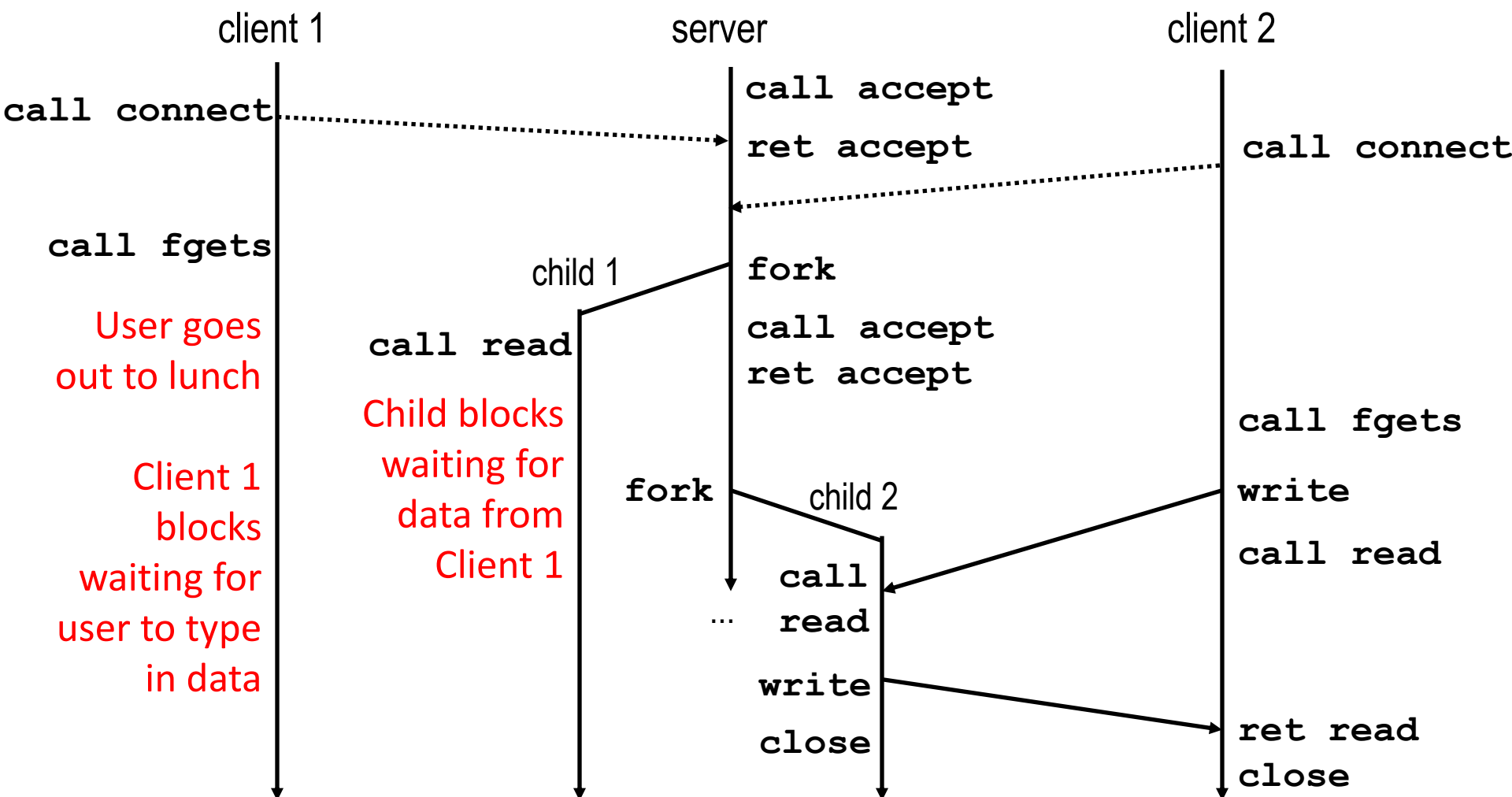
Approach #1: Process-based Servers

■ 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

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 */
        }
    }
}
```

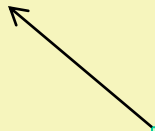
echoserverp.c

Making a Concurrent Echo Server

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{
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        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)
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    int listenfd, connfd;
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        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

```
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;
}
```

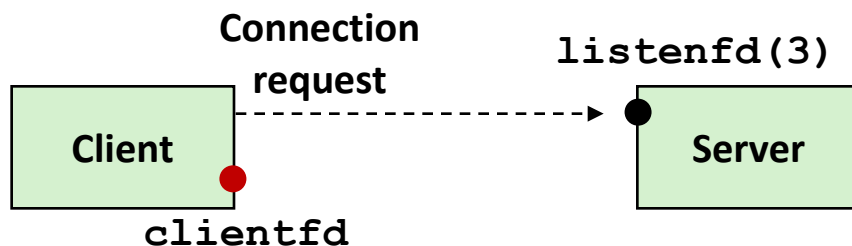
echoserverp.c

- Reap all zombie children

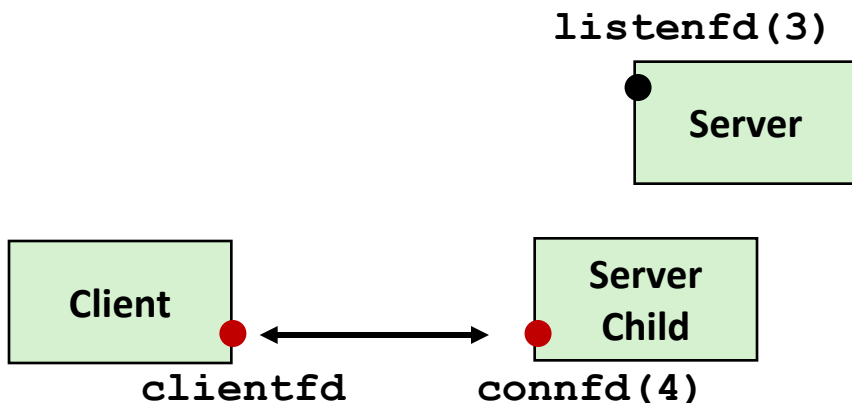
Concurrent Server: `accept` Illustrated



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

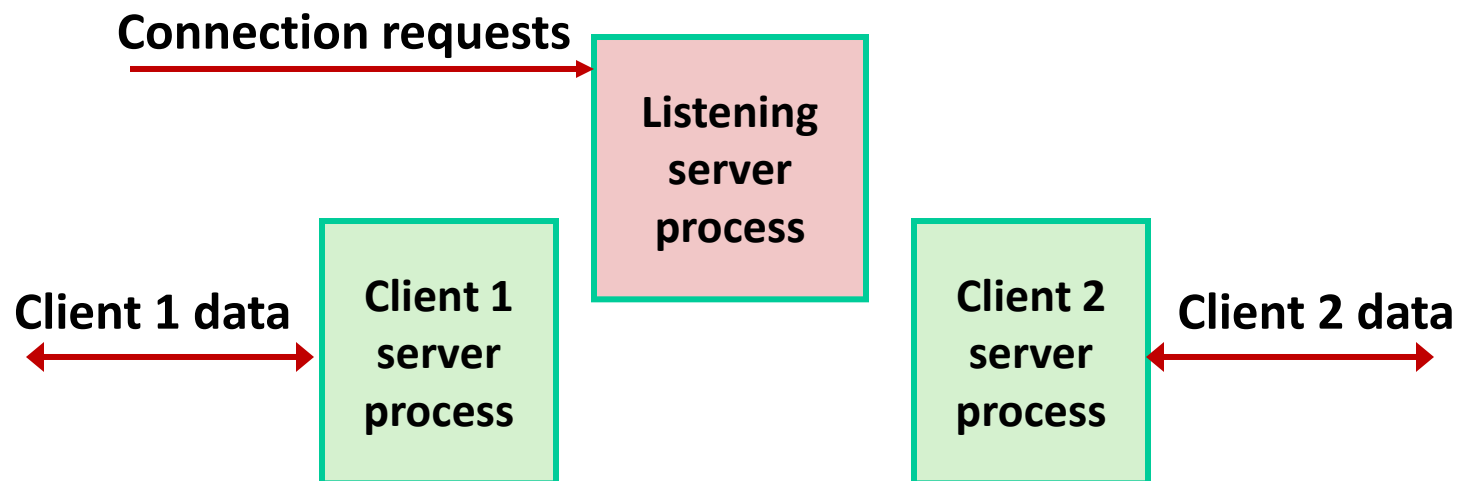


2. Client makes connection request by calling `connect`



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`

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

connfd's		
0	10	Active
1	7	
2	4	
3	-1	Inactive
4	-1	
5	12	
6	5	Active
7	-1	
8	-1	Never Used
9	-1	

Anything
happened?

Pending Inputs

listenfd = 3

connfd's	
10	
7	←
4	
-1	
-1	
12	←
5	←
-1	
-1	
-1	

Read and service

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

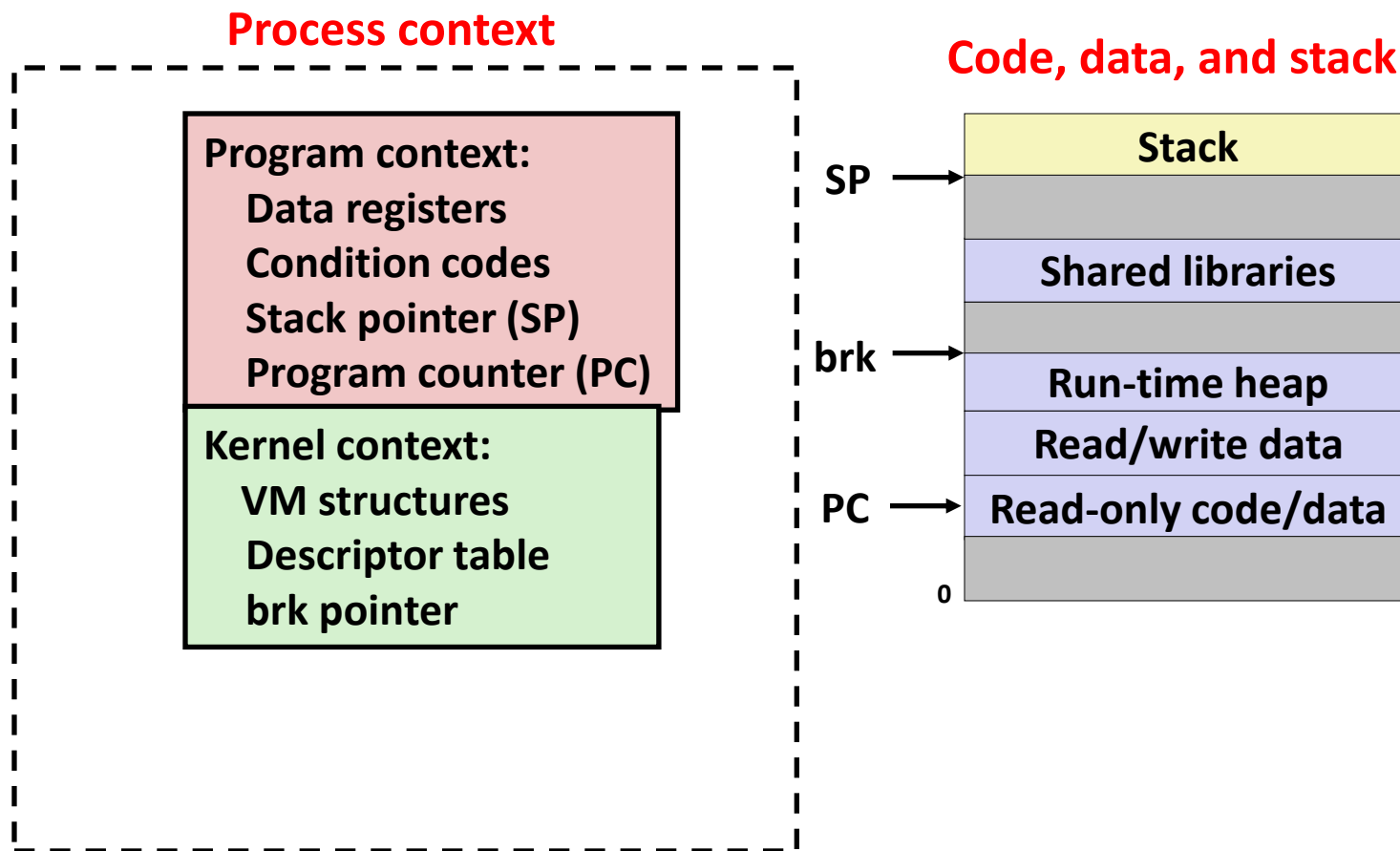
<https://canvas.cmu.edu/courses/47415/quizzes/143241>

Approach #3: Thread-based Servers

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

Traditional View of a Process

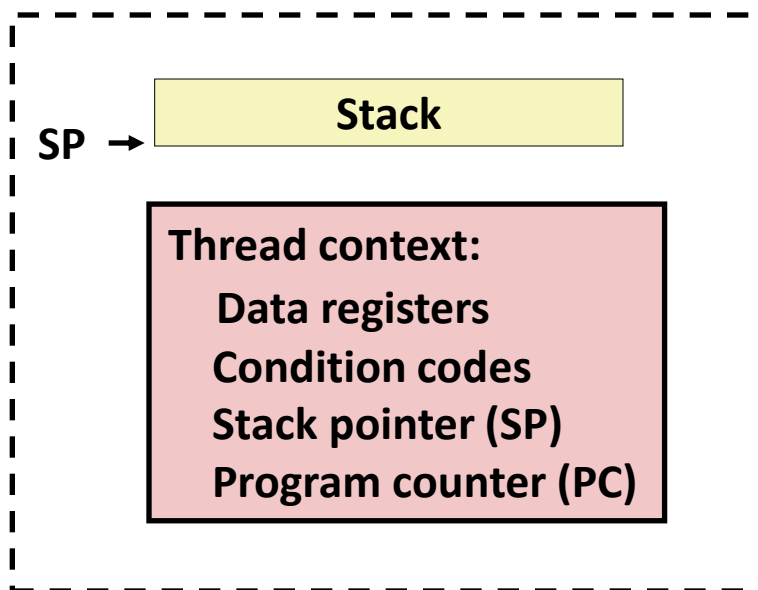
- Process = process context + code, data, and stack



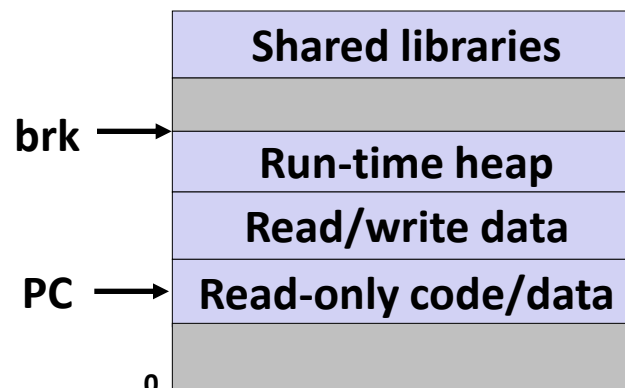
Alternate View of a Process

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

Thread (main thread)



Code, data, and kernel context



Kernel context:
VM structures
Descriptor table
brk pointer

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)

Shared code and data

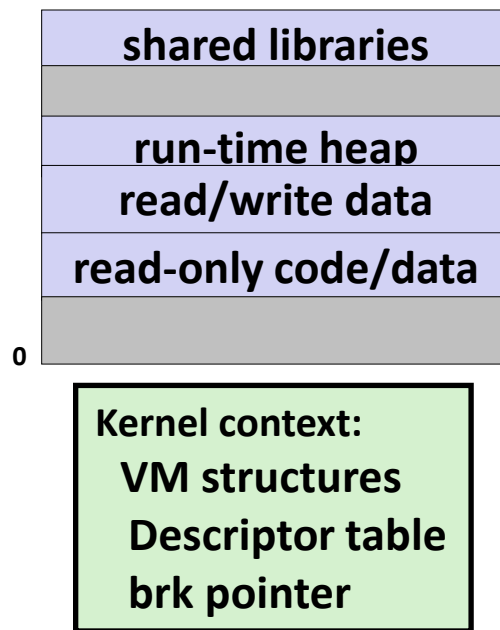
Thread 1 (main thread) Thread 2 (peer thread)

stack 1

stack 2

Thread 1 context:
Data registers
Condition codes
 SP_1
 PC_1

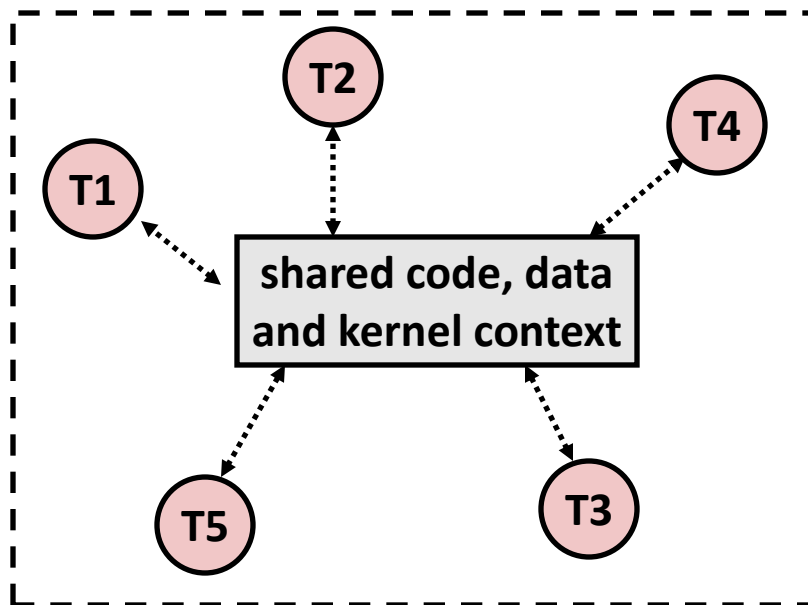
Thread 2 context:
Data registers
Condition codes
 SP_2
 PC_2



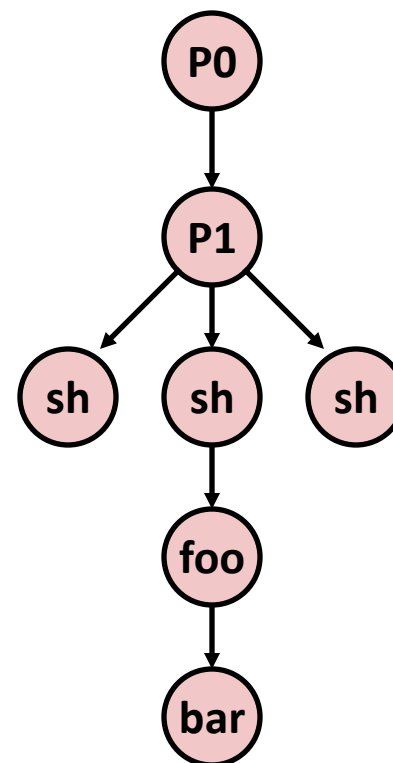
Logical View of Threads

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

Threads associated with process foo



Process hierarchy



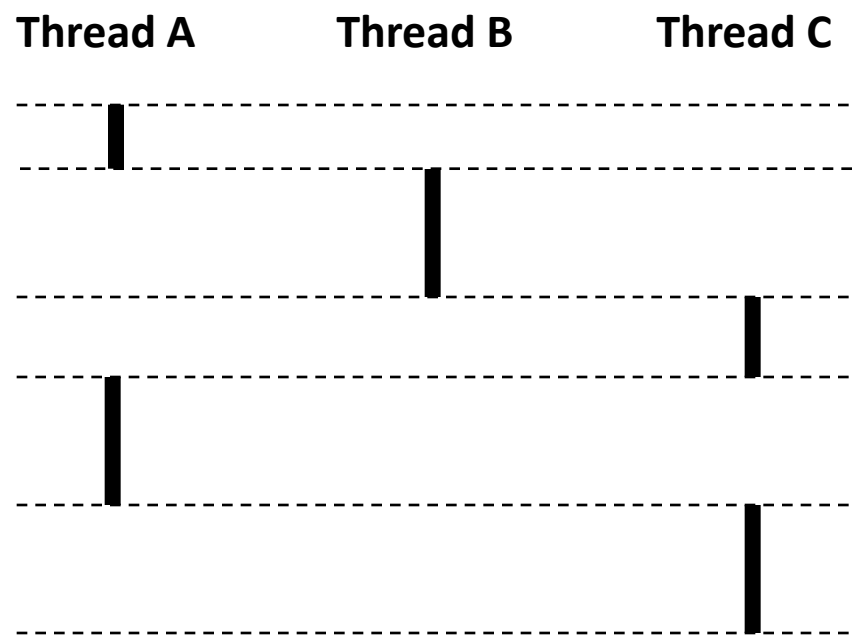
Concurrent Threads

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

- **Examples:**

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

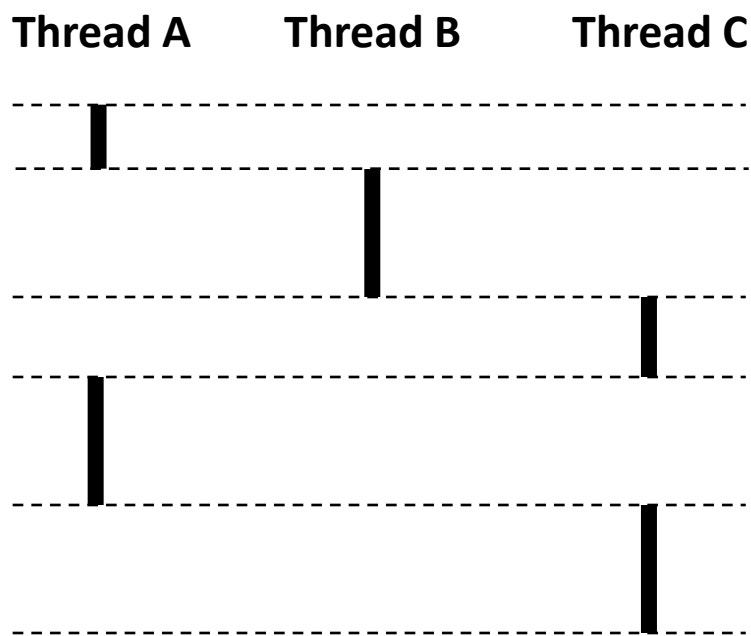
Time



Concurrent Thread Execution

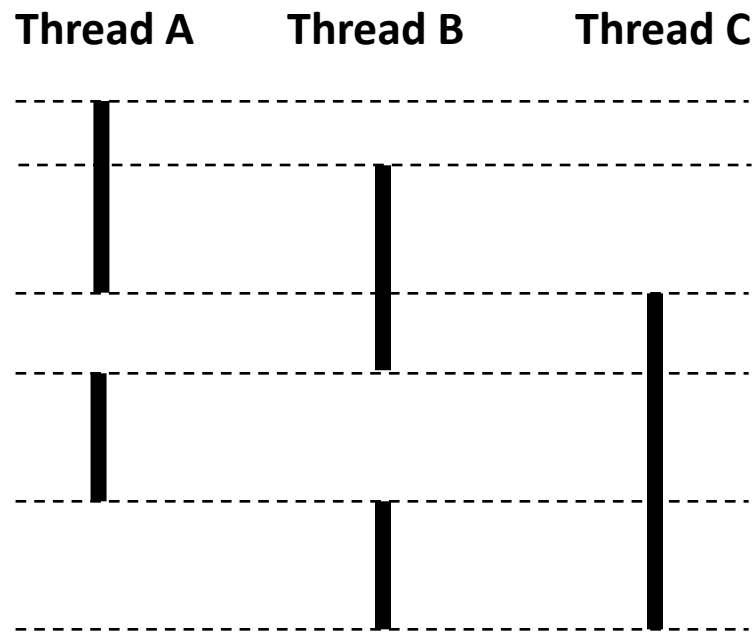
■ Single Core Processor

- Simulate parallelism by time slicing



■ Multi-Core Processor

- Can have true parallelism



Run 3 threads on 2 cores

Threads vs. Processes

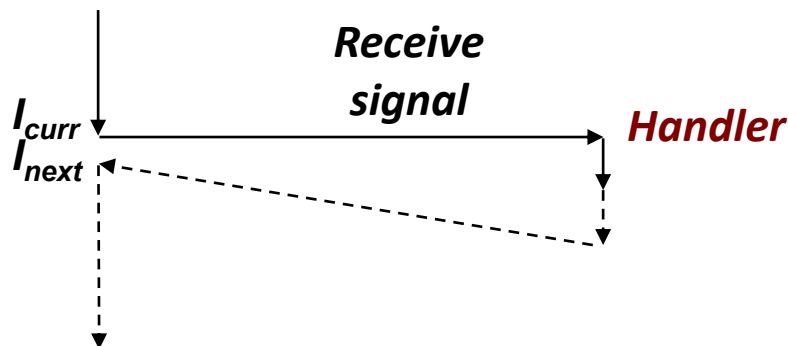
■ How threads and processes are similar

- 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

Thread API	Process API analogue
Creating and reaping...	
<code>pthread_create</code>	<code>fork</code>
<code>pthread_join</code>	<code>waitpid</code>
Determining your ID...	
<code>pthread_self</code>	<code>getpid</code>
Terminating execution...	
<code>pthread_exit</code>	<code>exit</code>
<code>return</code> from thread proc	<code>return</code> from main
Synchronizing operations...	
<code>pthread_mutex_lock</code>	[no exact analogue]
<code>pthread_mutex_unlock</code>	

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;  
}
```

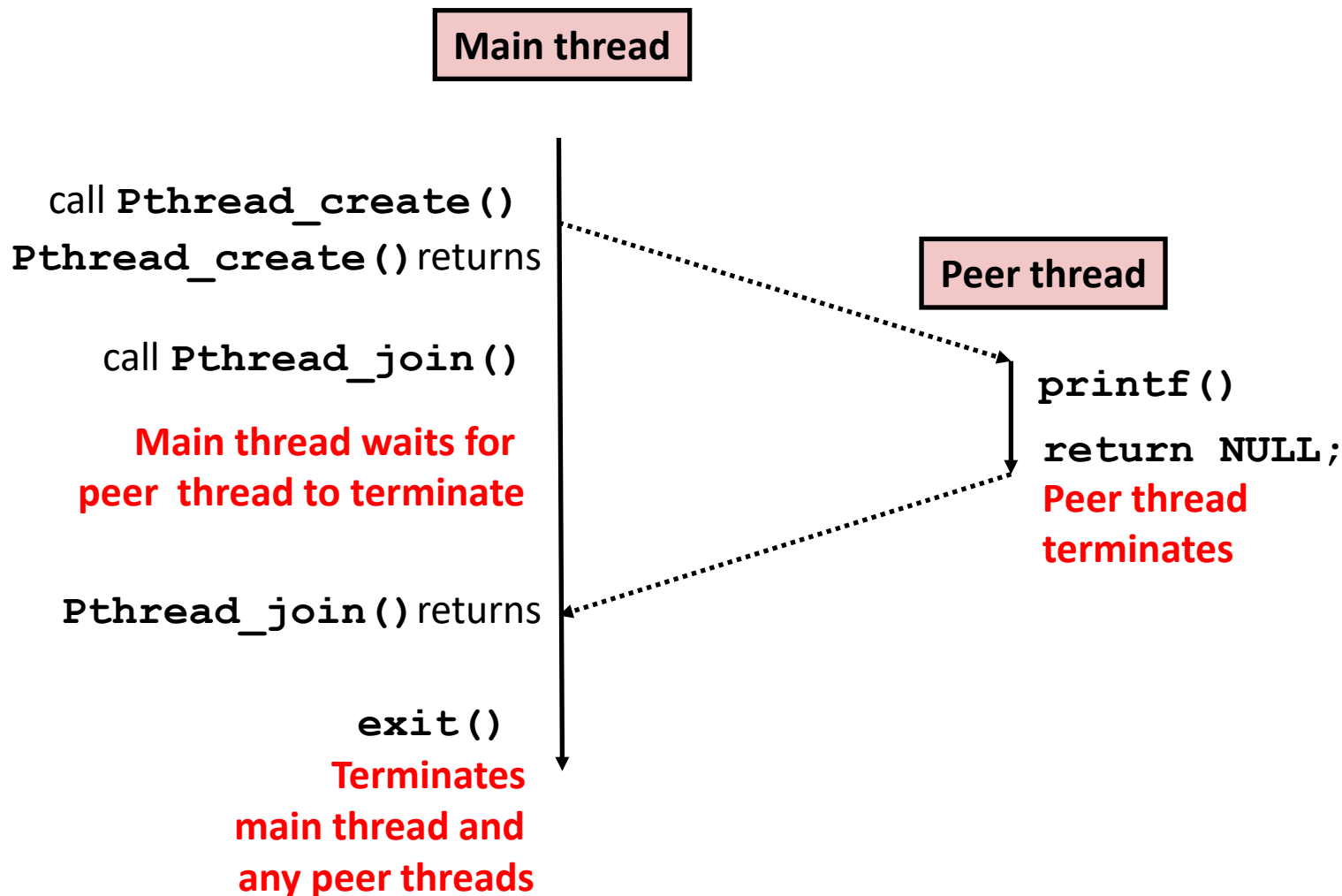
hello.c

Thread ID**Thread attributes
(usually NULL)****Thread routine****Thread arguments
(void *p)****Return value
(void **p)**

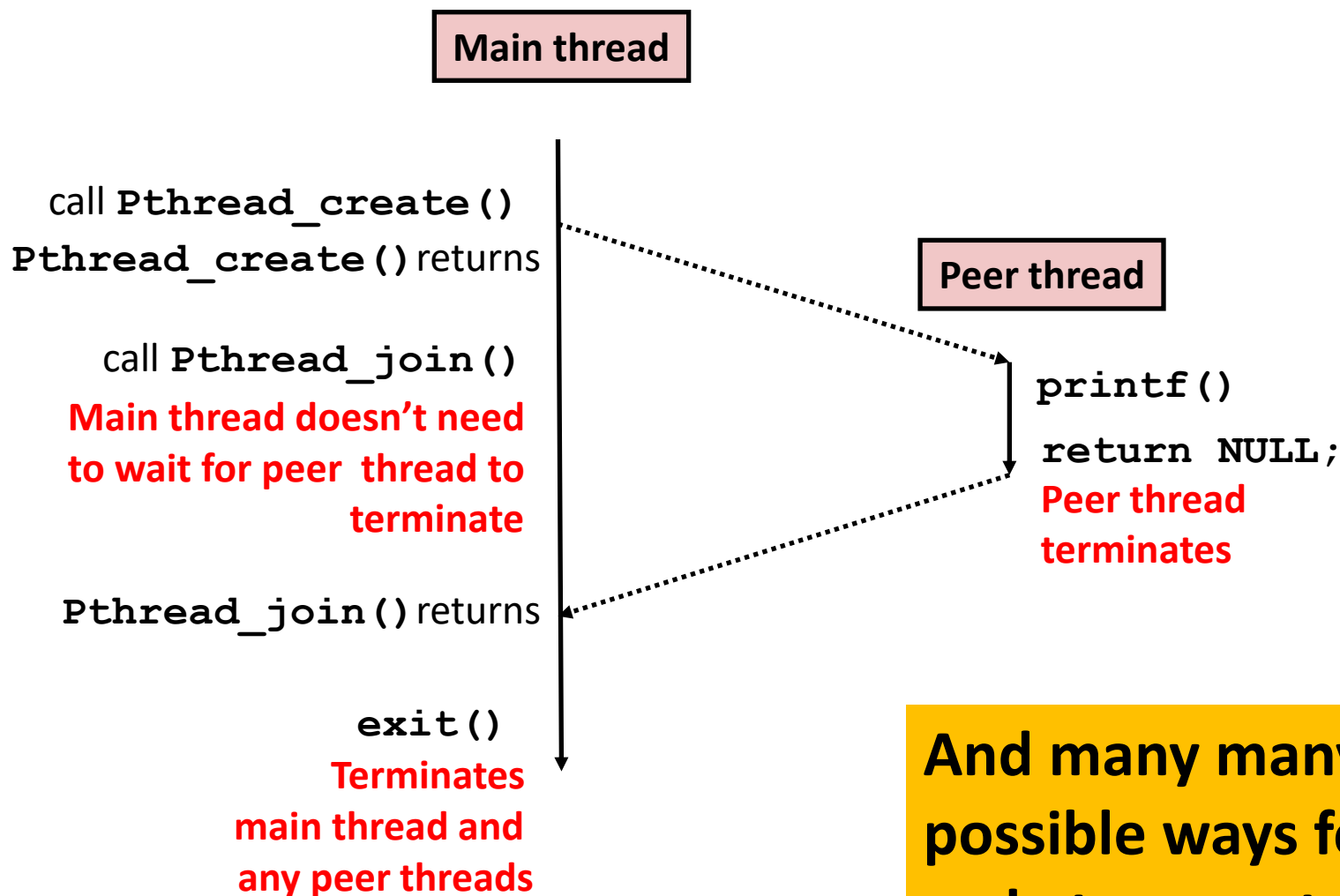
```
void *thread(void *vargp) /* thread routine */  
{  
    printf("Hello, world!\n");  
    return NULL;  
}
```

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

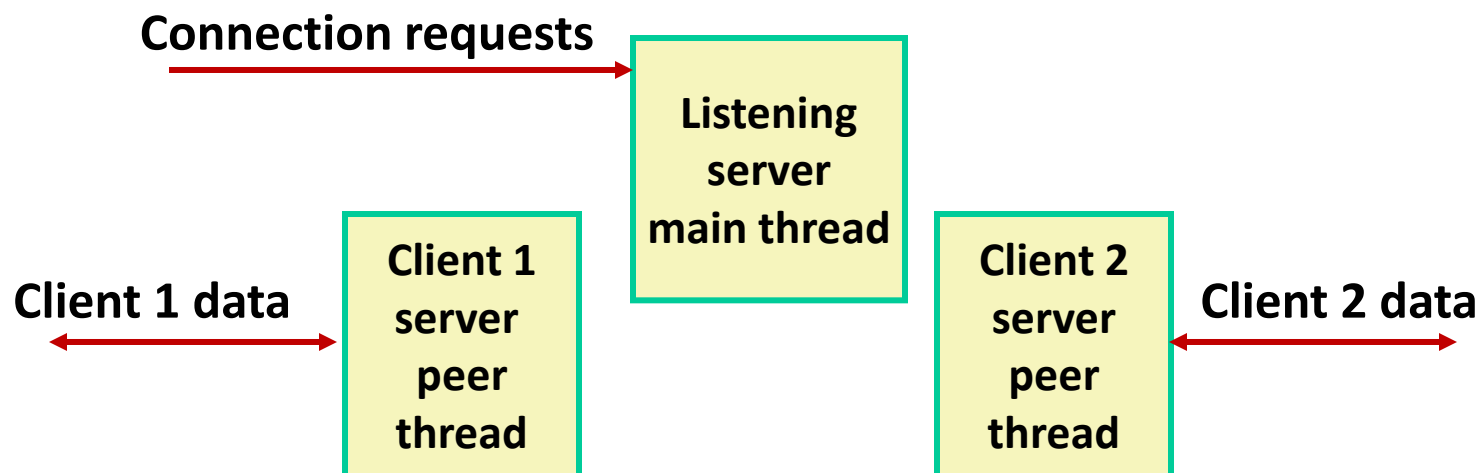
- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of **Malloc()** ! [but not **Free()**]

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

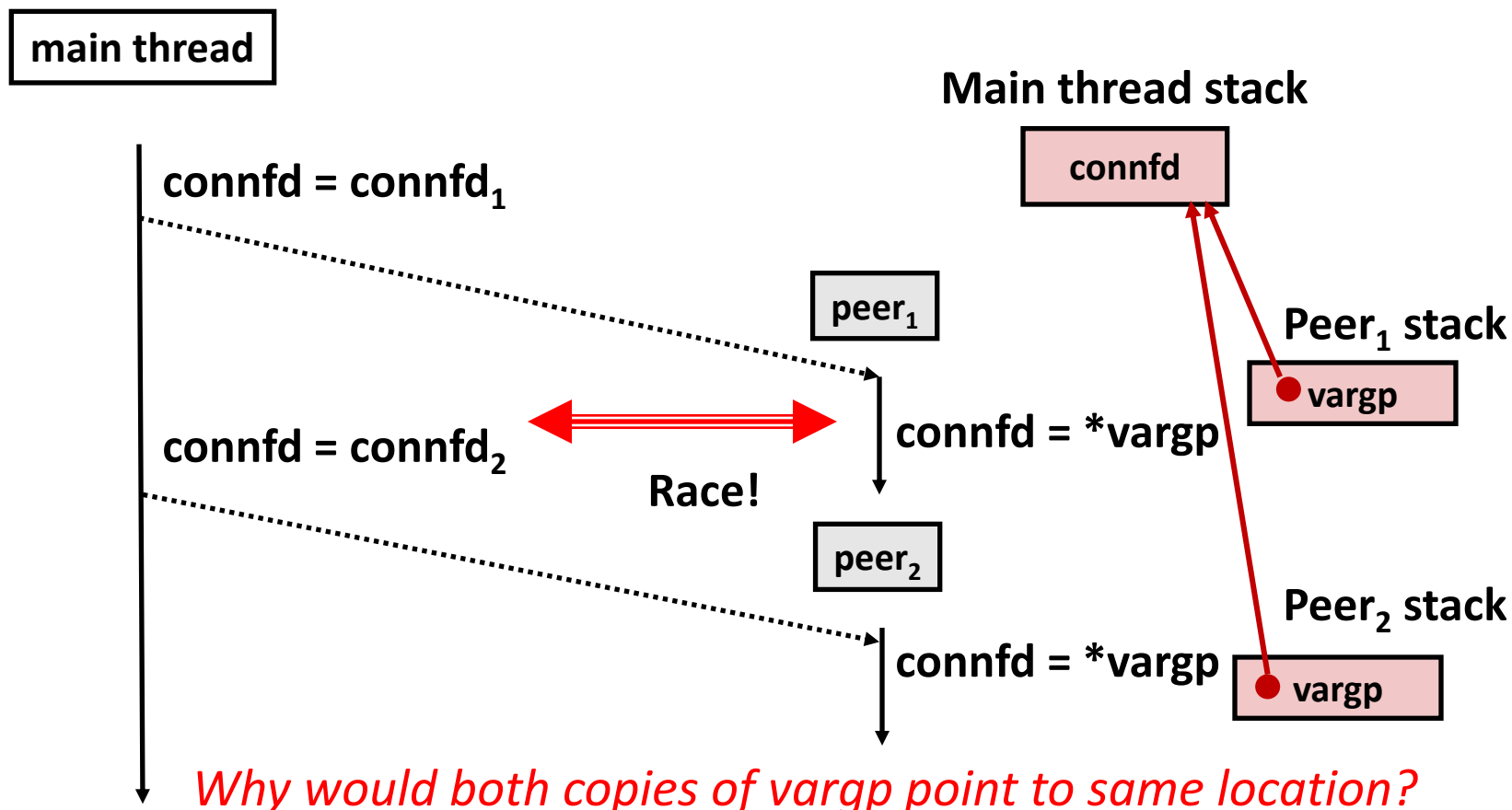
- For example, passing pointer to main thread's stack
 - `Pthread_create(&tid, NULL, thread, (void *)&connfd);`

■ 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)

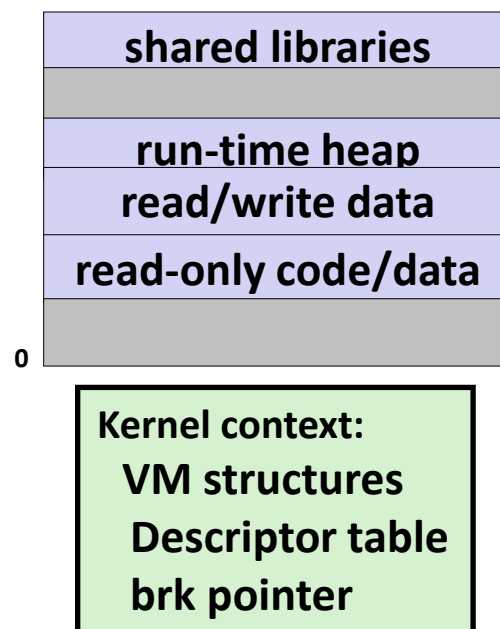
stack 1

stack 2

Thread 1 context:
Data registers
Condition codes
 SP_1
 PC_1

Thread 2 context:
Data registers
Condition codes
 SP_2
 PC_2

Shared code and data



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:

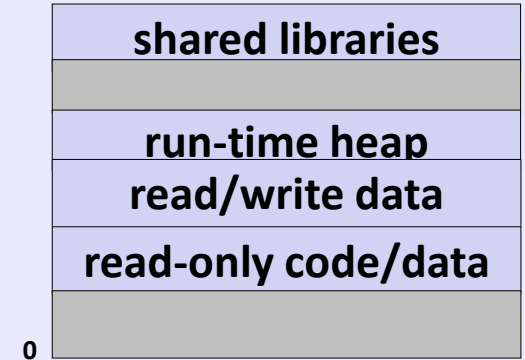
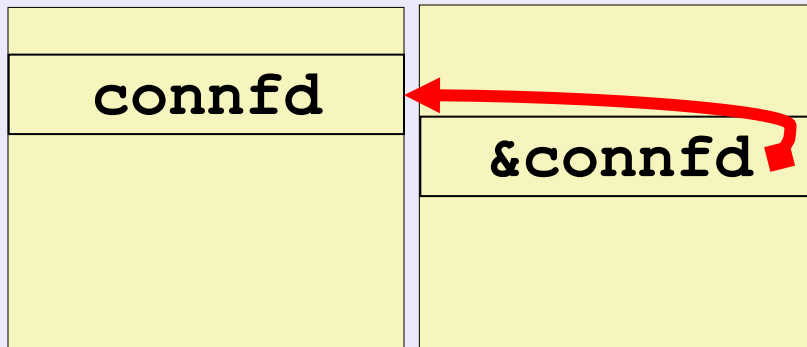
- Data registers
- Condition codes
- SP₁
- PC₁

Thread 2 context:

- Data registers
- Condition codes
- SP₂
- PC₂

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
- SP₁
- PC₁

Thread 2 context:

- Data registers
- Condition codes
- SP₂
- PC₂

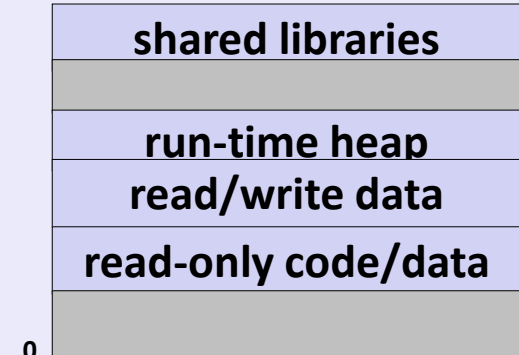
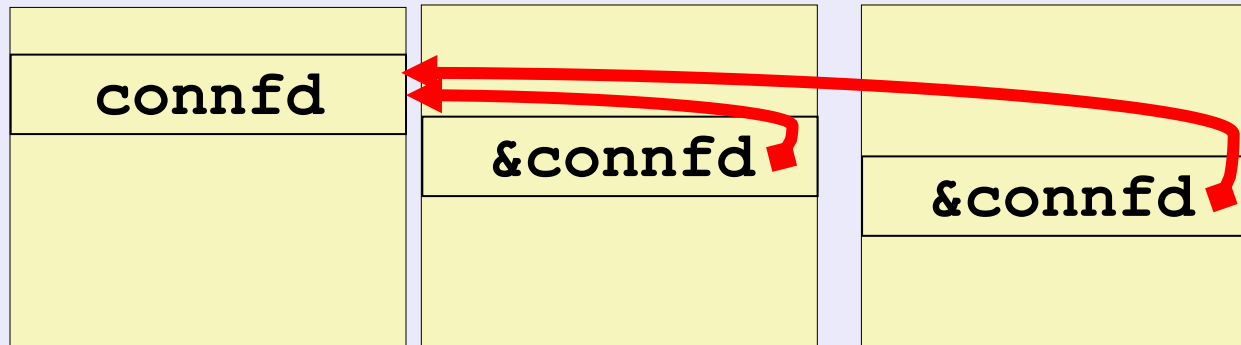
Thread 3 context:

- Data registers
- Condition codes
- SP₂
- PC₂

Thread 1

Thread 2

Thread 3



Kernel context:

- VM structures
- Descriptor table
- brk pointer

Thread 1 context:
Data registers
Condition codes
 SP_1
 PC_1

Thread 2 context:
Data registers
Condition codes
 SP_2
 PC_2

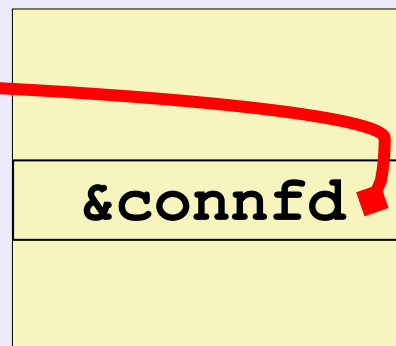
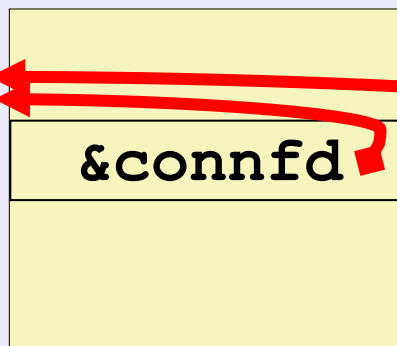
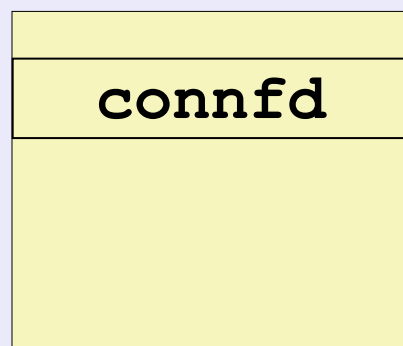
Thread
Data
Con
 SP_2
 PC_2

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

Thread 1

Thread 2

Th



shared libraries

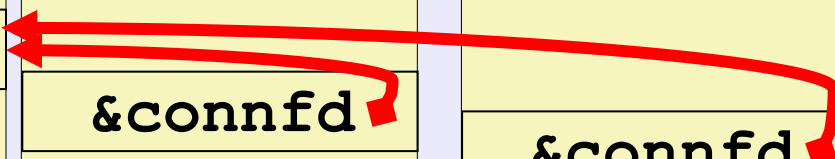
run-time heap

read/write data

read-only code/data

0

Kernel context:
VM structures
Descriptor table
brk pointer



Could this race occur?

Main

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

Thread

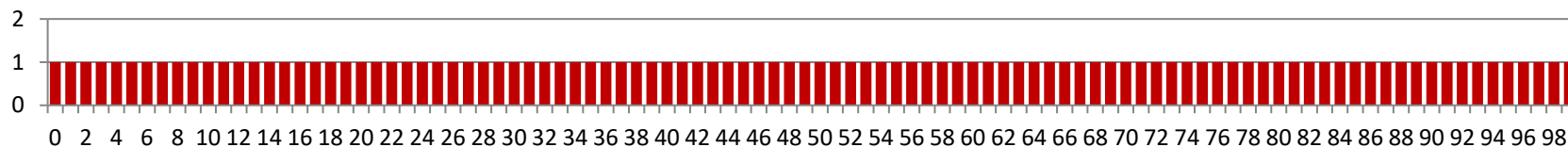
```
void *thread(void *vargp)
{
    int i = *((int *)vargp);
    Pthread_detach(pthread_self());
    save_value(i);
    return NULL;
}
```

■ Race Test

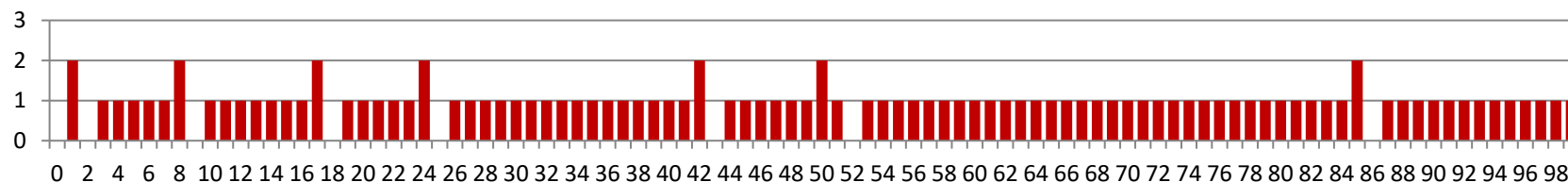
- If no race, then each thread would get different value of **i**
- Set of saved values would consist of one copy each of 0 through 99

Experimental Results

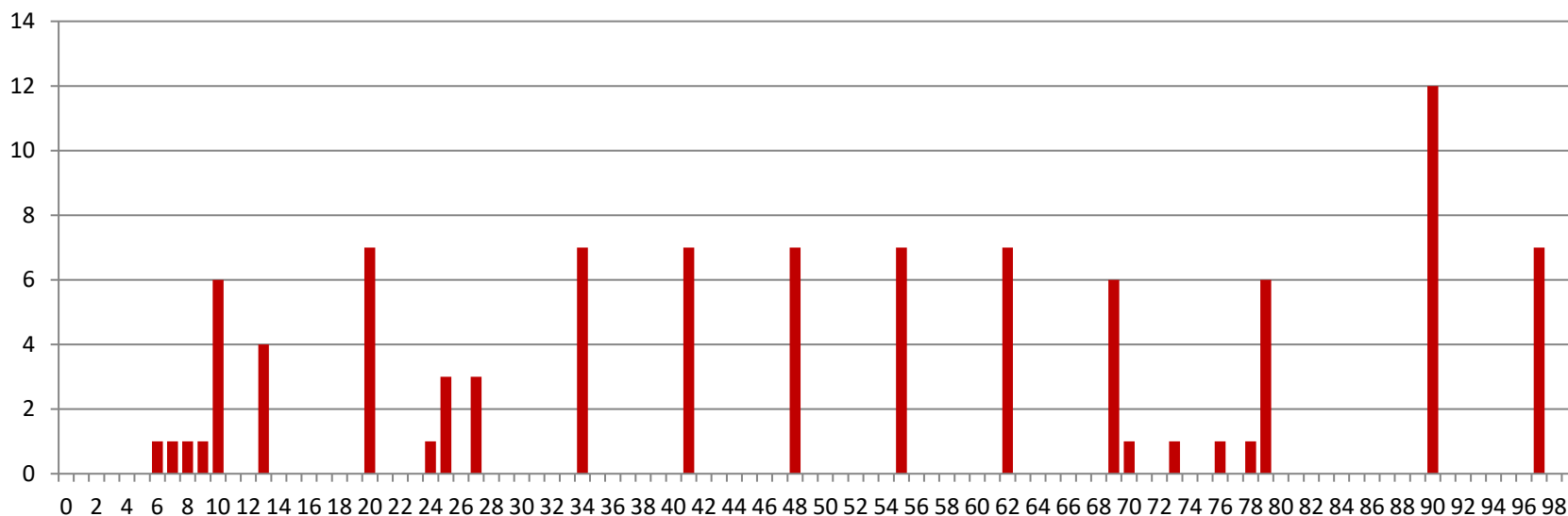
No Race



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