Concurrent Programming

15-213/15-513: Introduction to Computer Systems
23rd Lecture, July 23, 2024

Instructors:

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Concurrent Programming is Hard!

- The human mind tends to be sequential

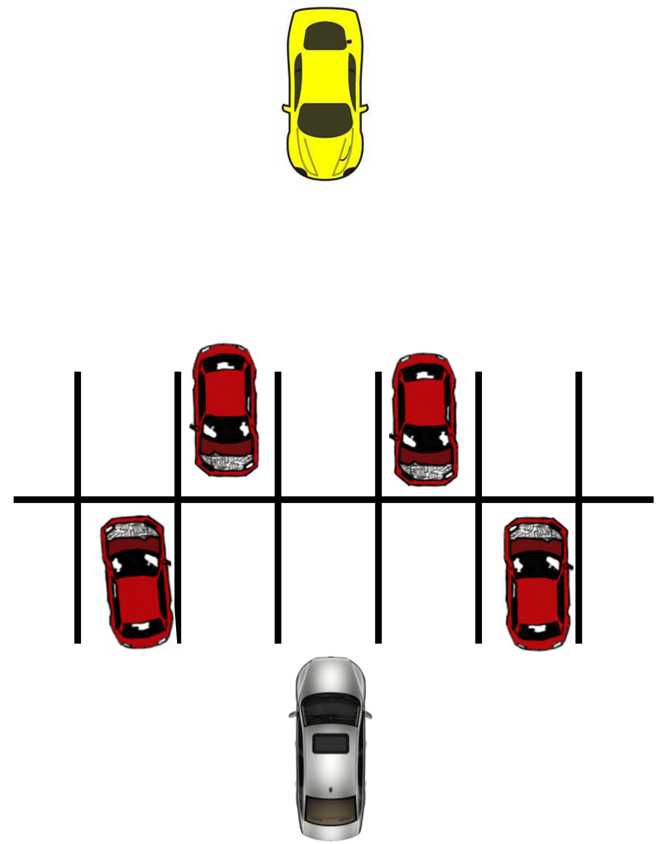
- The notion of time is often misleading

- 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

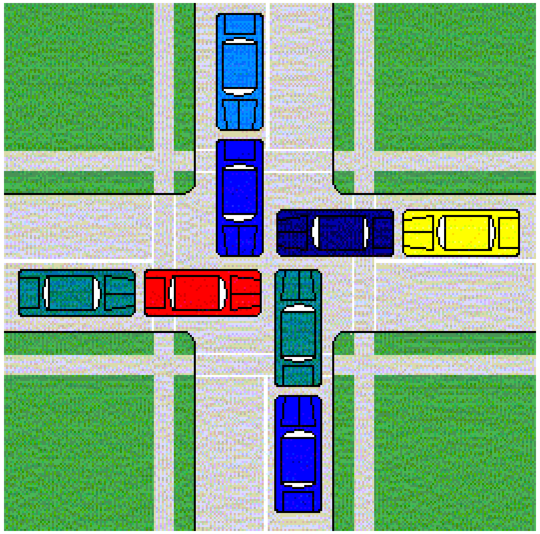


```
/* Global shared variable */
volatile long cnt = 0; /* Counter */
void *thread(void *vargp)
{
    long i, niters =
                *((long *)vargp);

    for (i = 0; i < niters; i++)
        cnt++;

    return NULL;
}
```

Deadlock

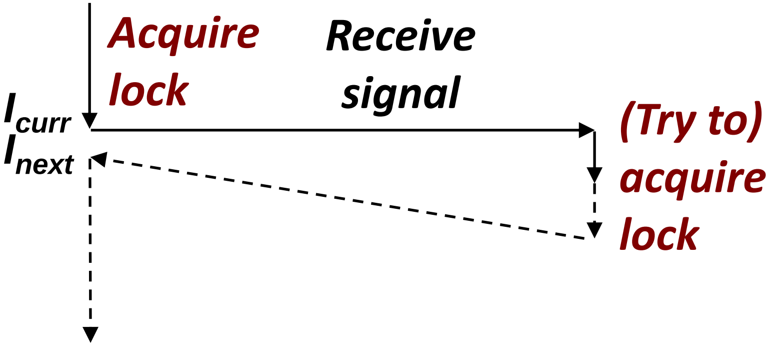


Deadlock

- 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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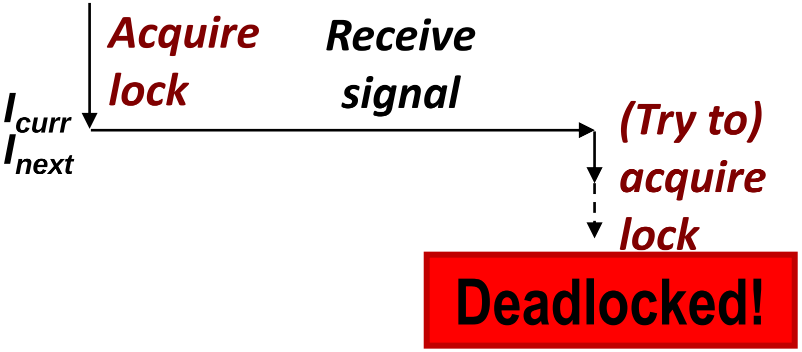

- What if signal handler interrupts call to printf?

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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        pid_t pid = fork();
        if (pid == 0)
            _exit(0);
        // in parent
        printf("Child #%d=%d sta
               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

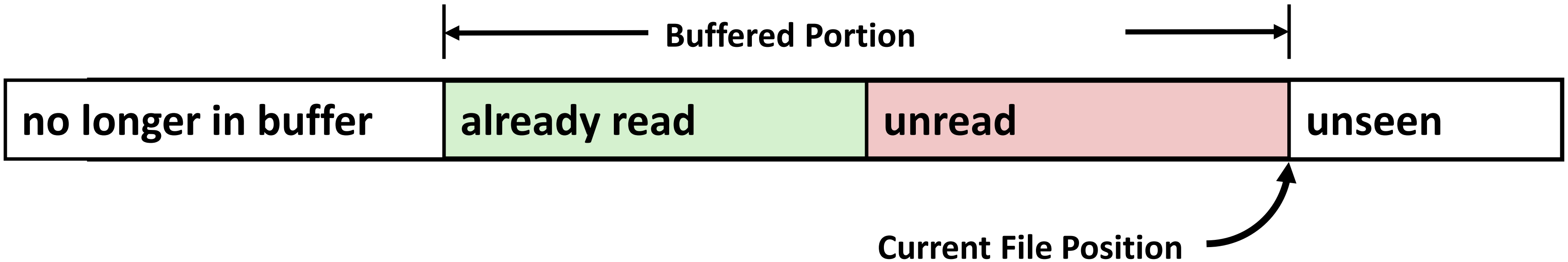
```
static void sigchld(int unused) {
    int status;
    pid_t pid;
    while ((pid = waitpid(-1, &status, WNOHANG)) > 0) {
        printf("Child %d exited with status %04x\n", pid, status);
    }
}

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?

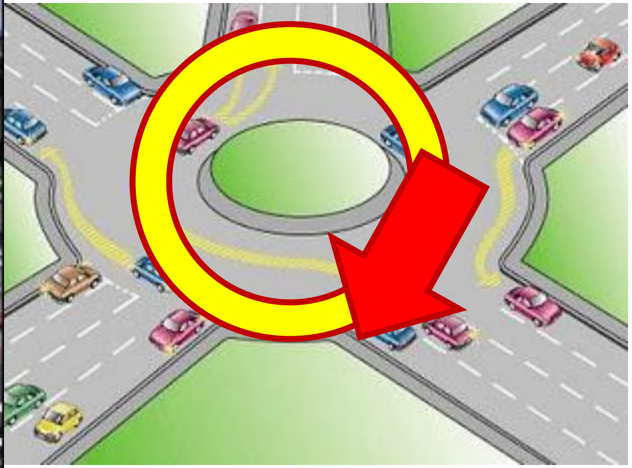
- Printf (and fprintf, sprintf) implement *buffered* I/O



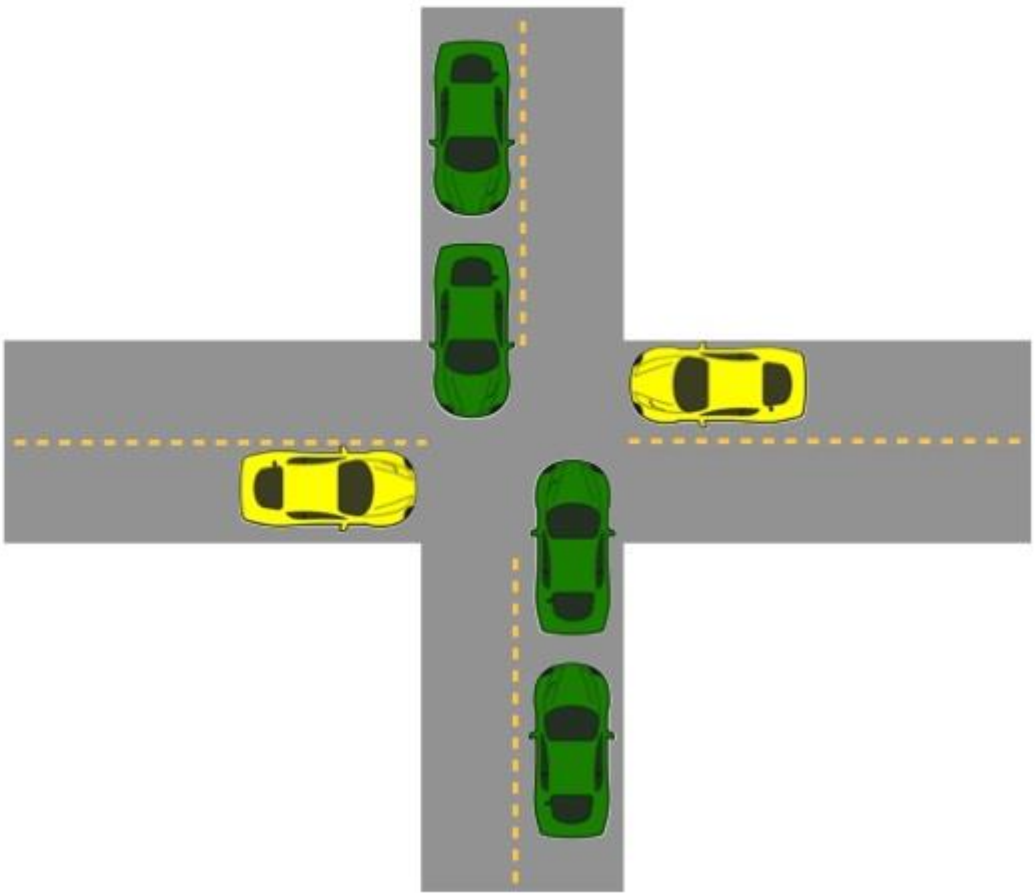
- Require locks to access the shared buffers

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!

- **Classical problem classes of concurrent programs:**
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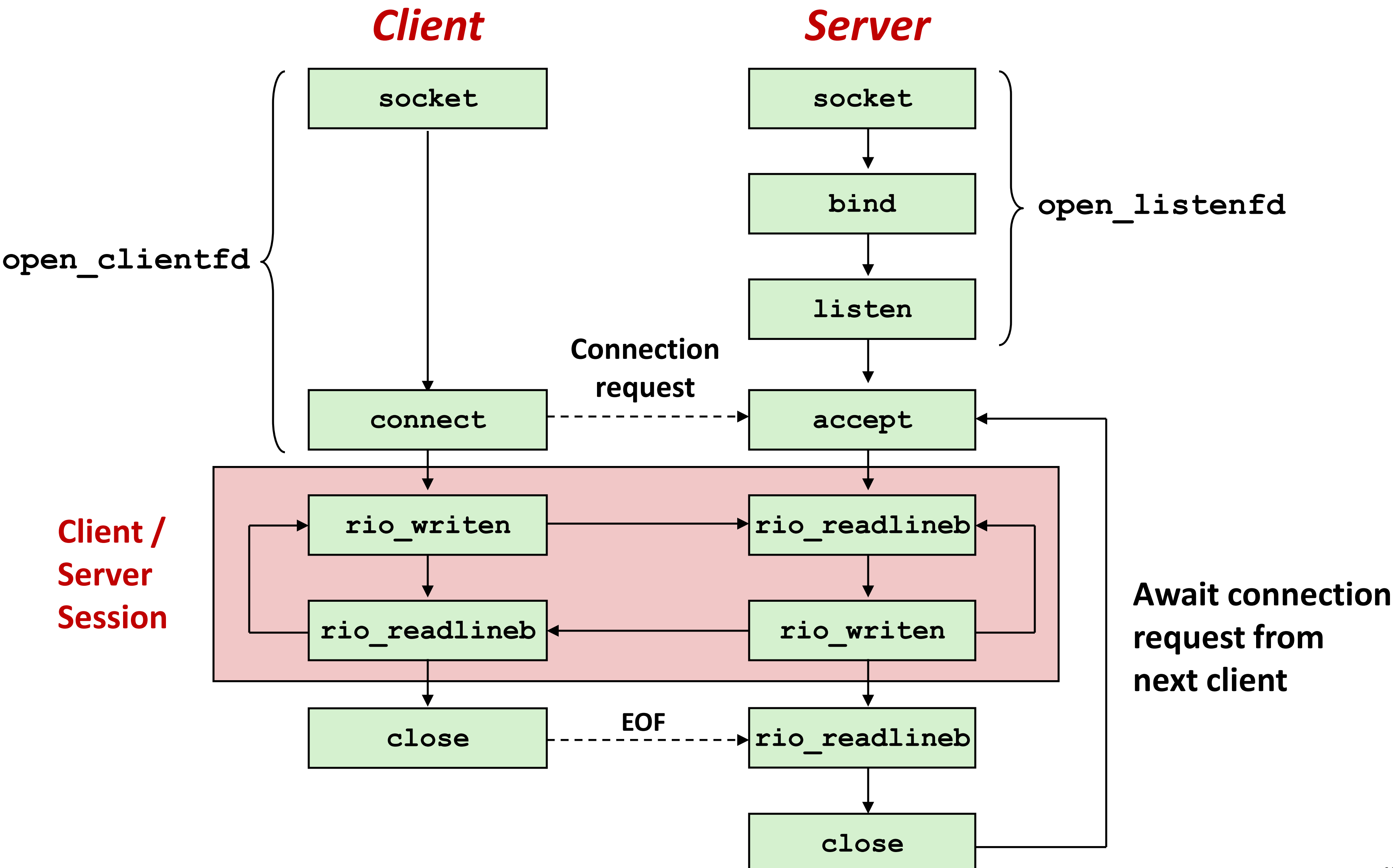
    - Example: who gets the last seat on the airplane?
  - ***Deadlock:*** improper resource allocation prevents forward progress
    - Example: traffic gridlock
  - ***Livelock / Starvation / Fairness***: external events and/or system scheduling decisions can prevent sub-task progress
    - Example: people 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 …

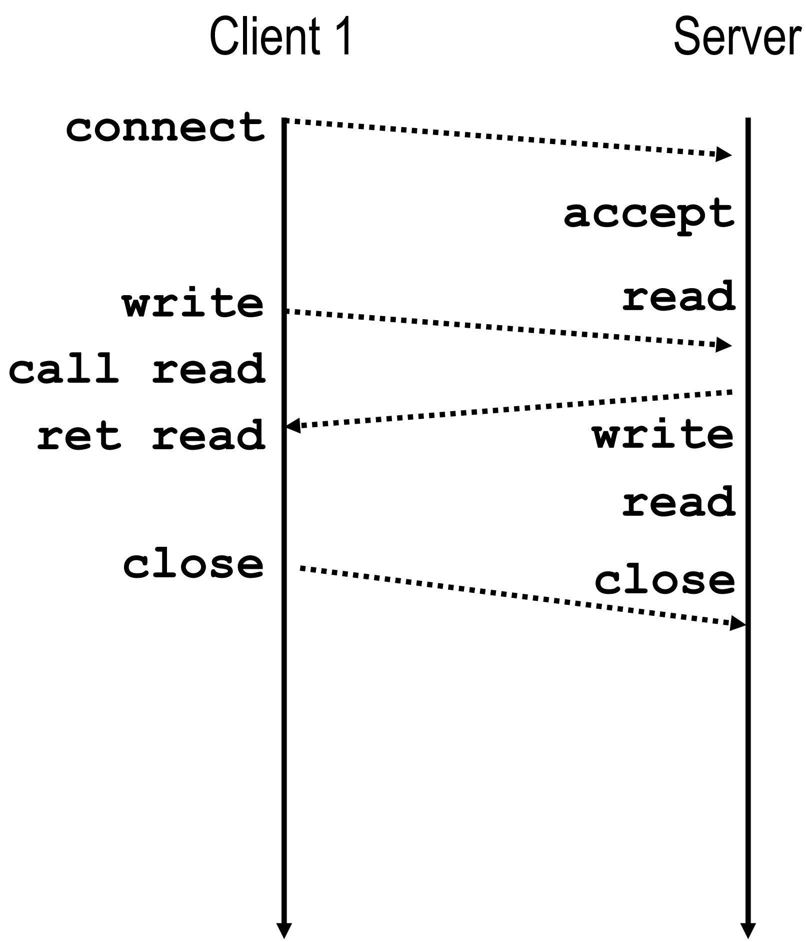
it can be useful and more and more necessary!

Reminder: Iterative Echo Server



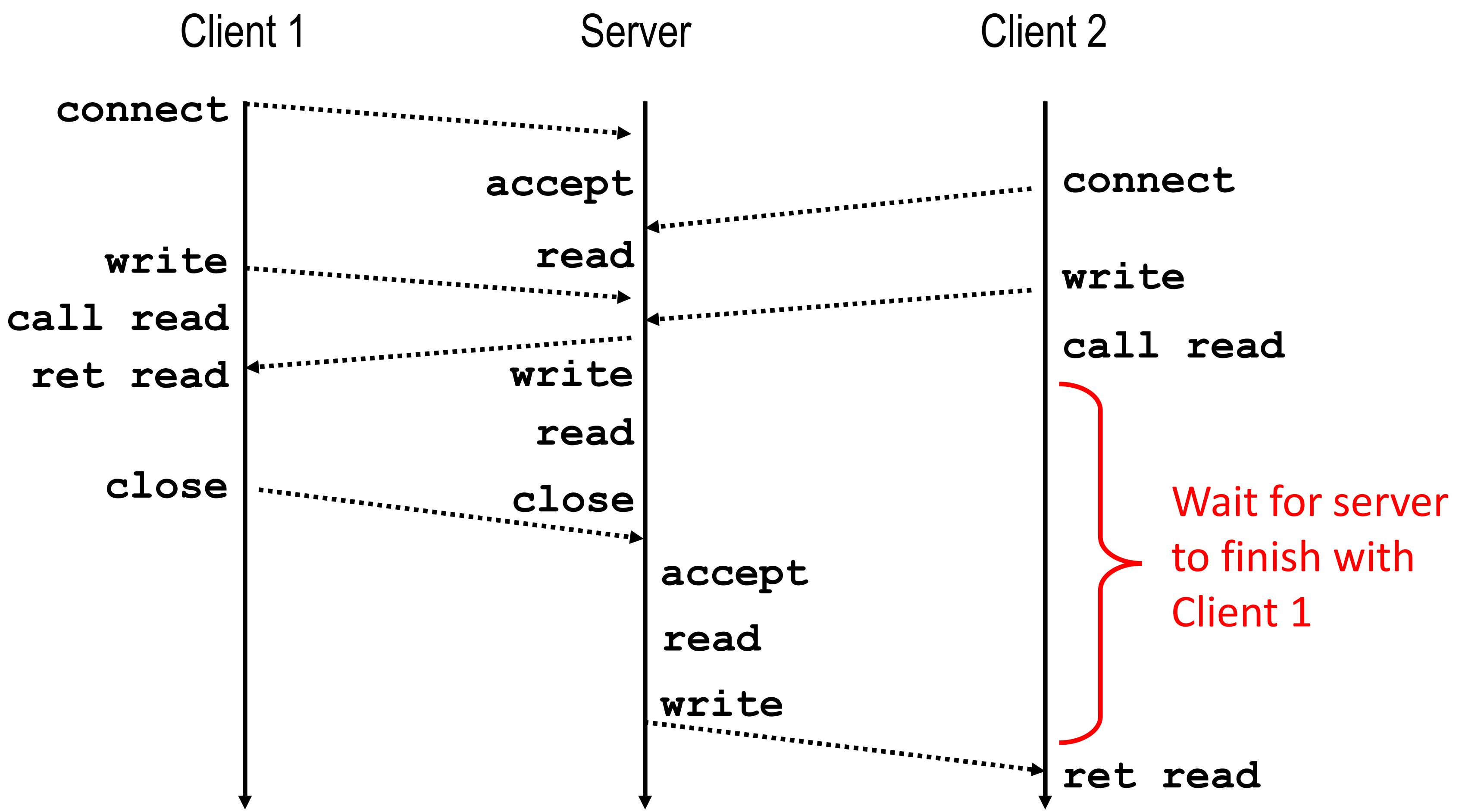
Iterative Servers

- Iterative servers process one request at a time



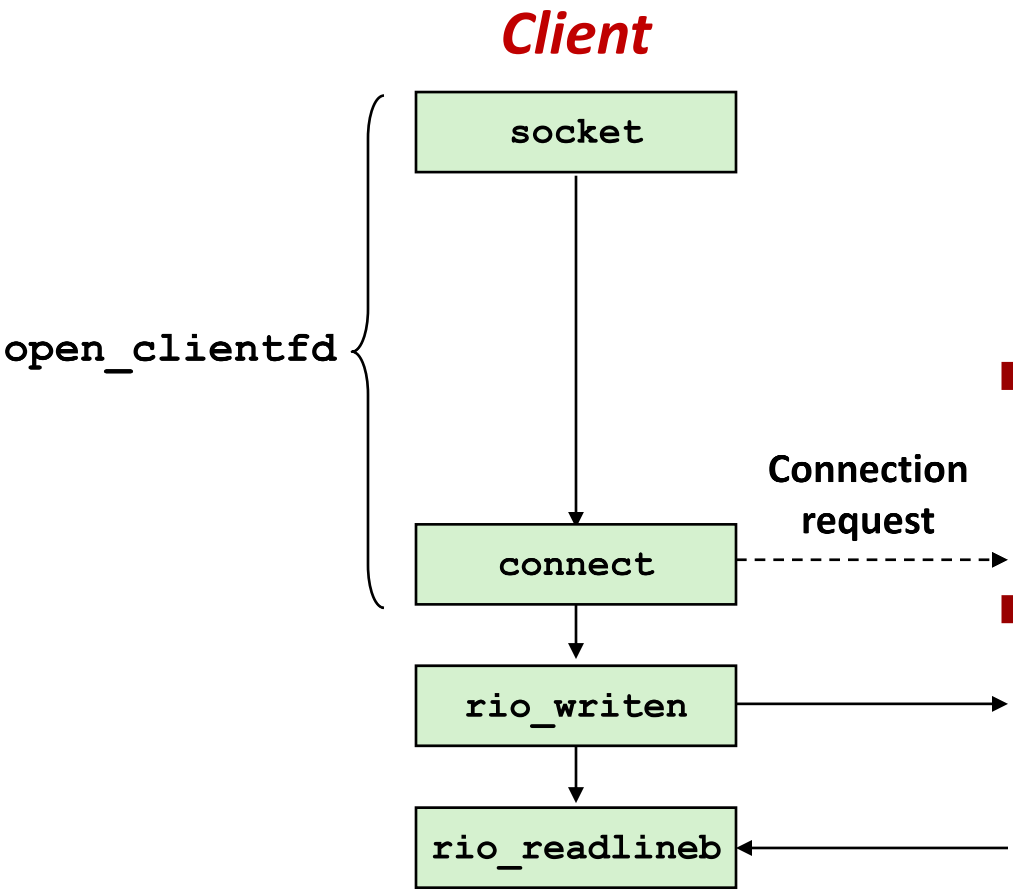
Iterative Servers

- Iterative servers process one request at a time



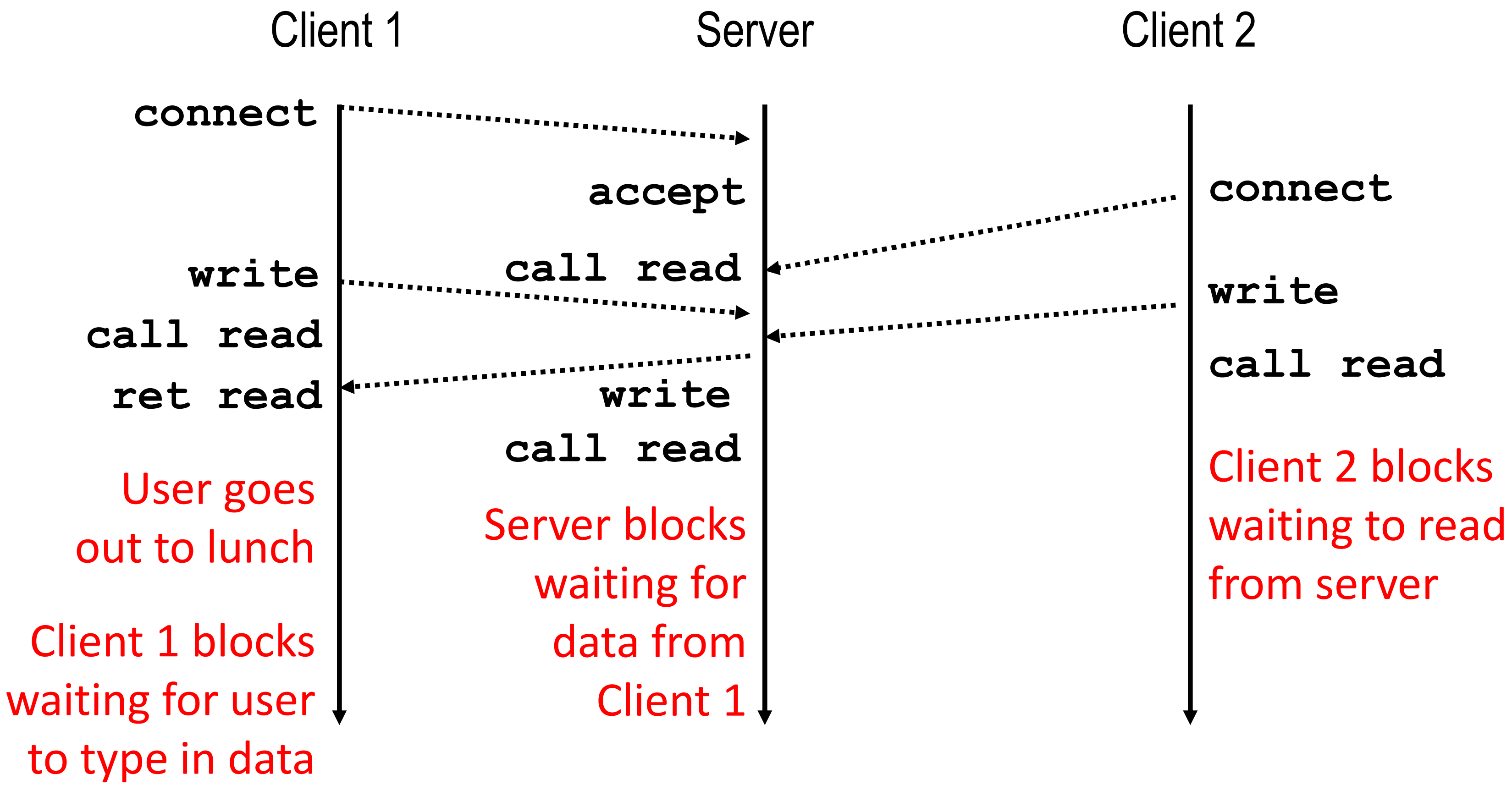
Where Does Second Client Block?

- **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

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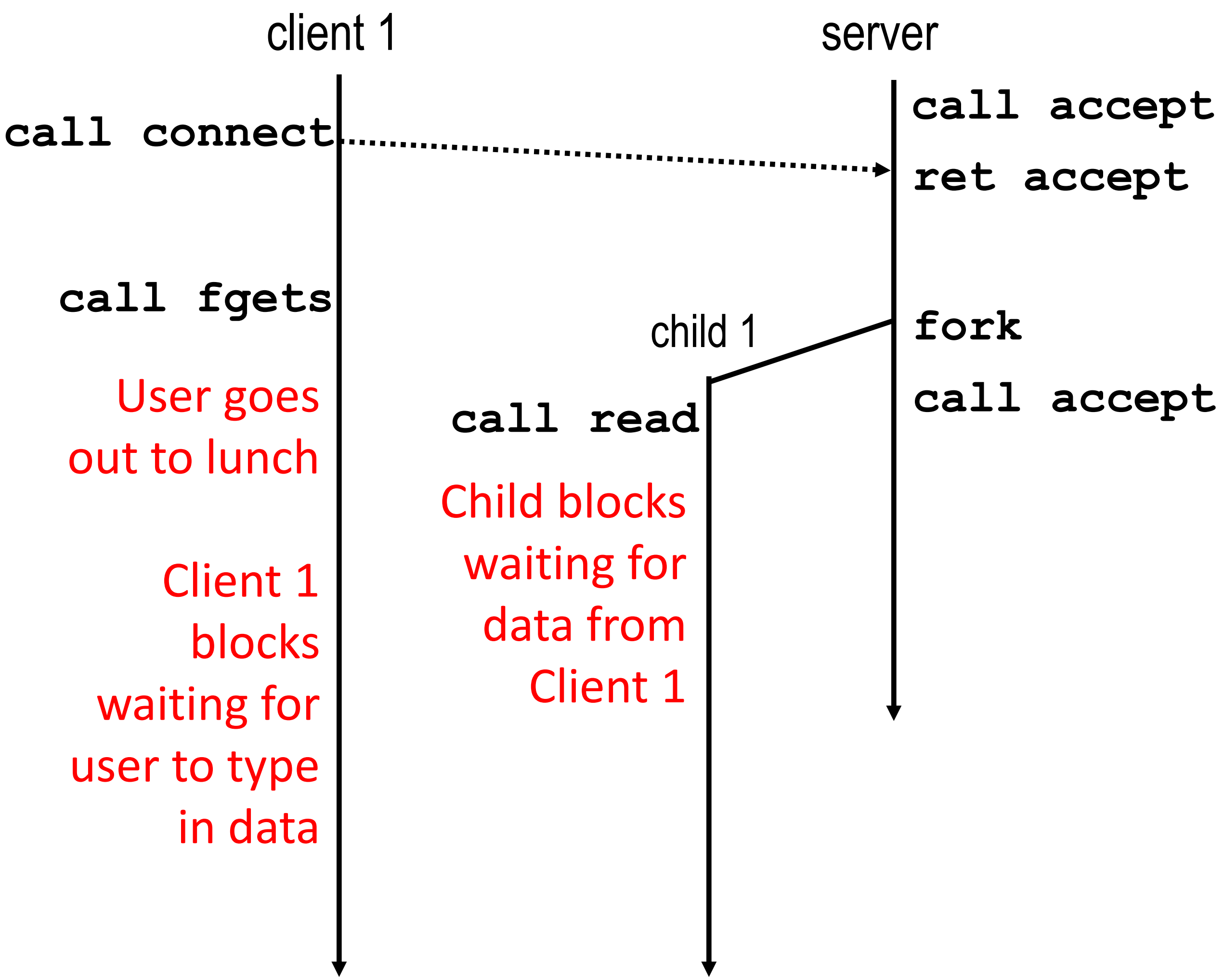
Approach #1: Process-based Servers

- Spawn separate process for each client



Approach #1: Process-based Servers

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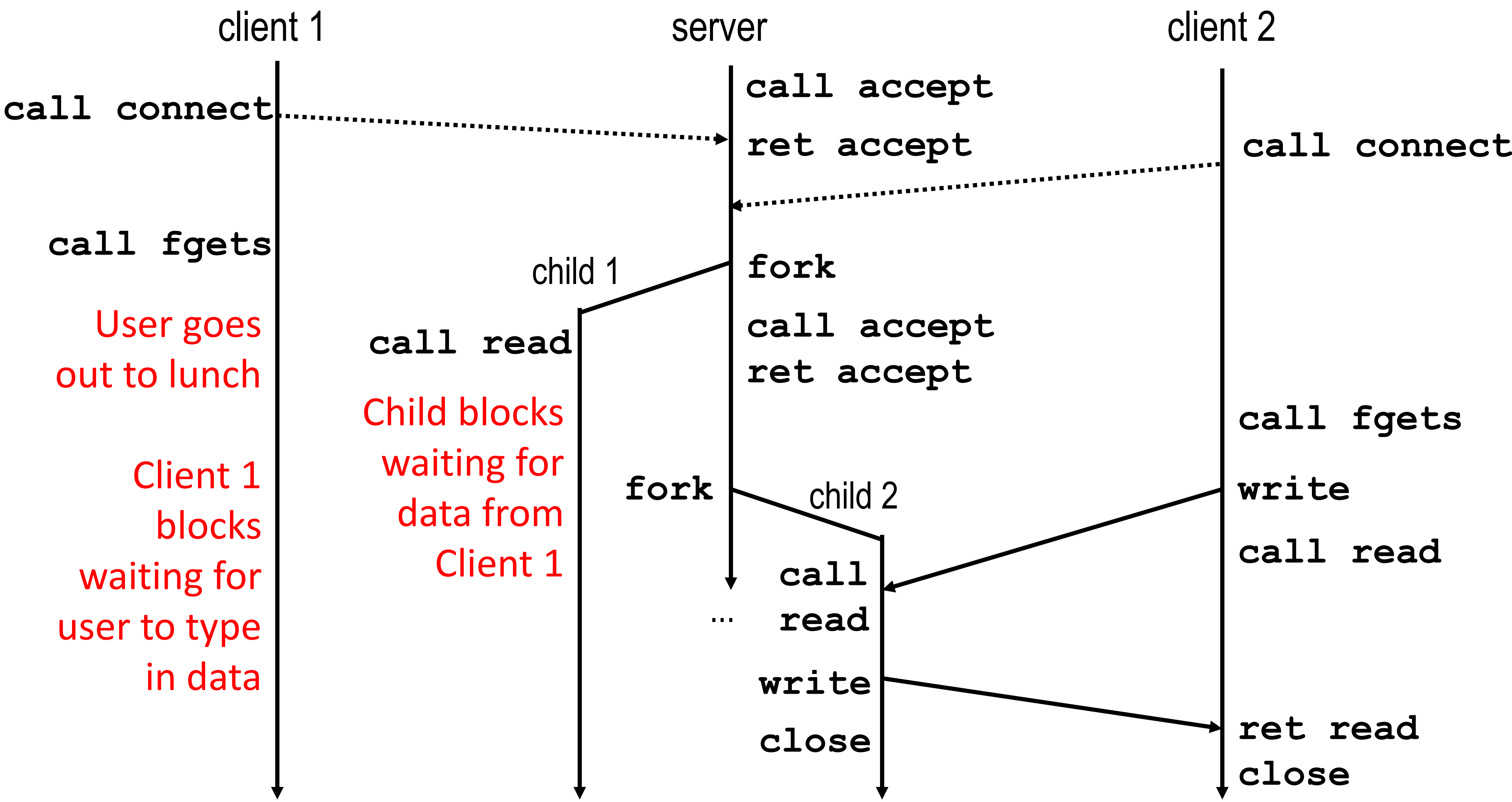

Iterative Echo Server

```
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;
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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) {

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

    }
}
```

echoserverp.c

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        Close(connfd); /* Parent closes connected socket (important!) */
    }
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```

echoserverp.c

Why?

Making a Concurrent Echo Server

```
int main(int argc, char **argv)
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    listenfd = Open_listenfd(argv[1]);
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        if (Fork() == 0) {
            Close(listenfd); /* Child closes its listening socket */
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            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!) */
    }
}
```

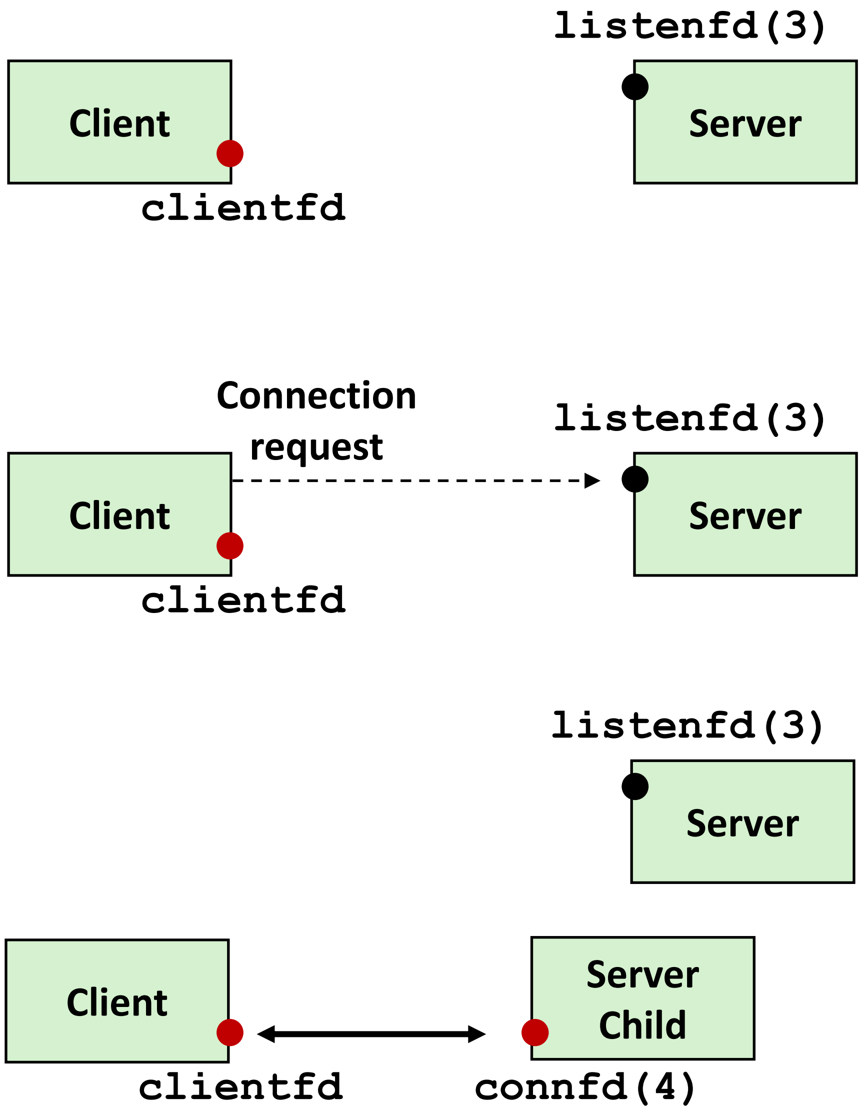
echoserverp.c

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

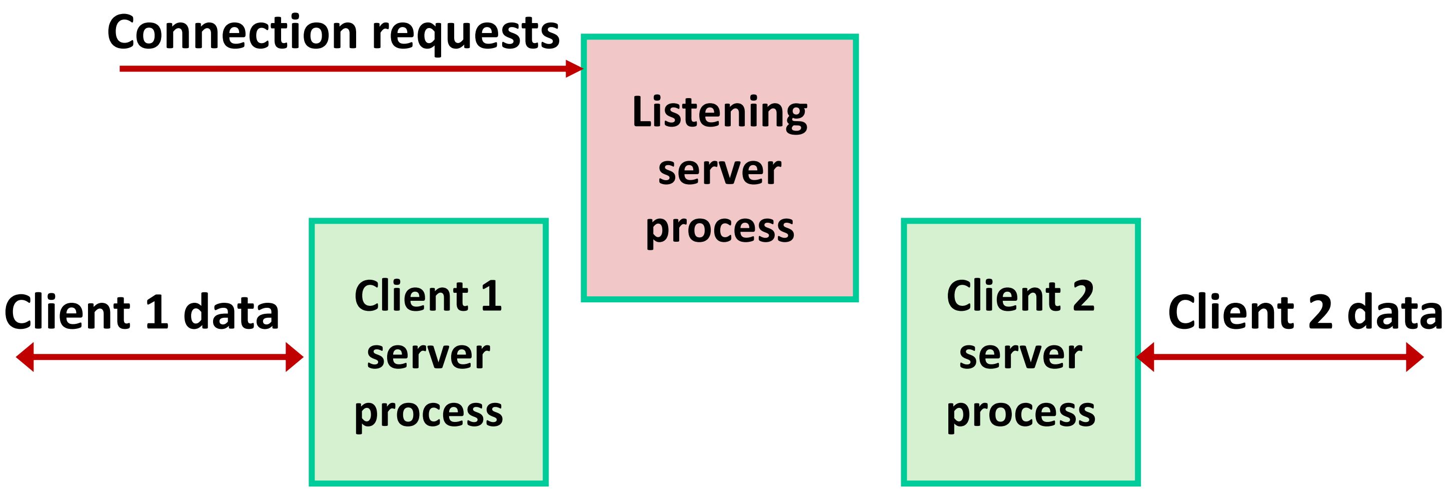


1. Server blocks in `accept`, waiting for connection request on listening descriptor `listenfd`

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`

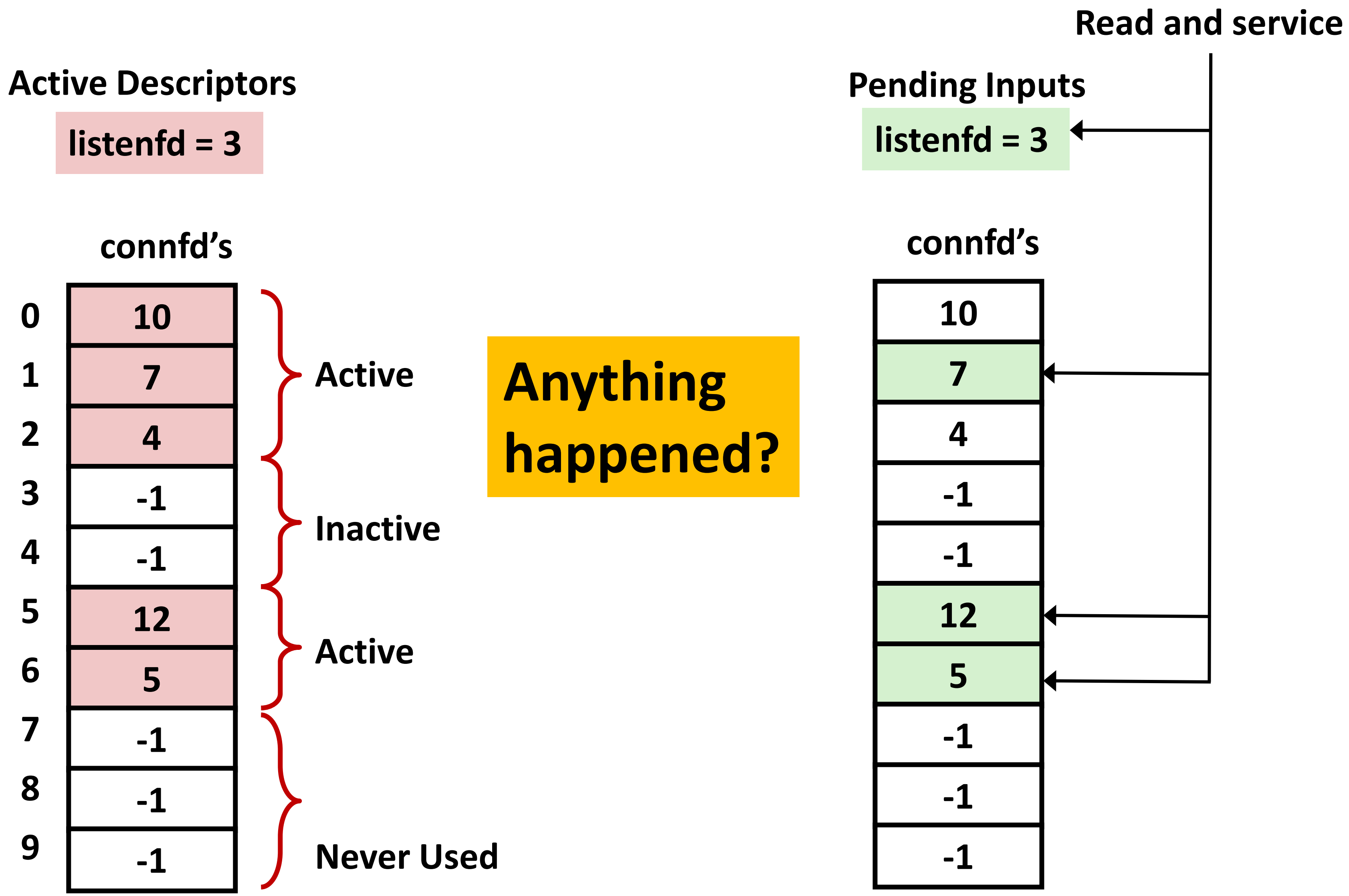
Pros and Cons of Process-based Servers

- **+ 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



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

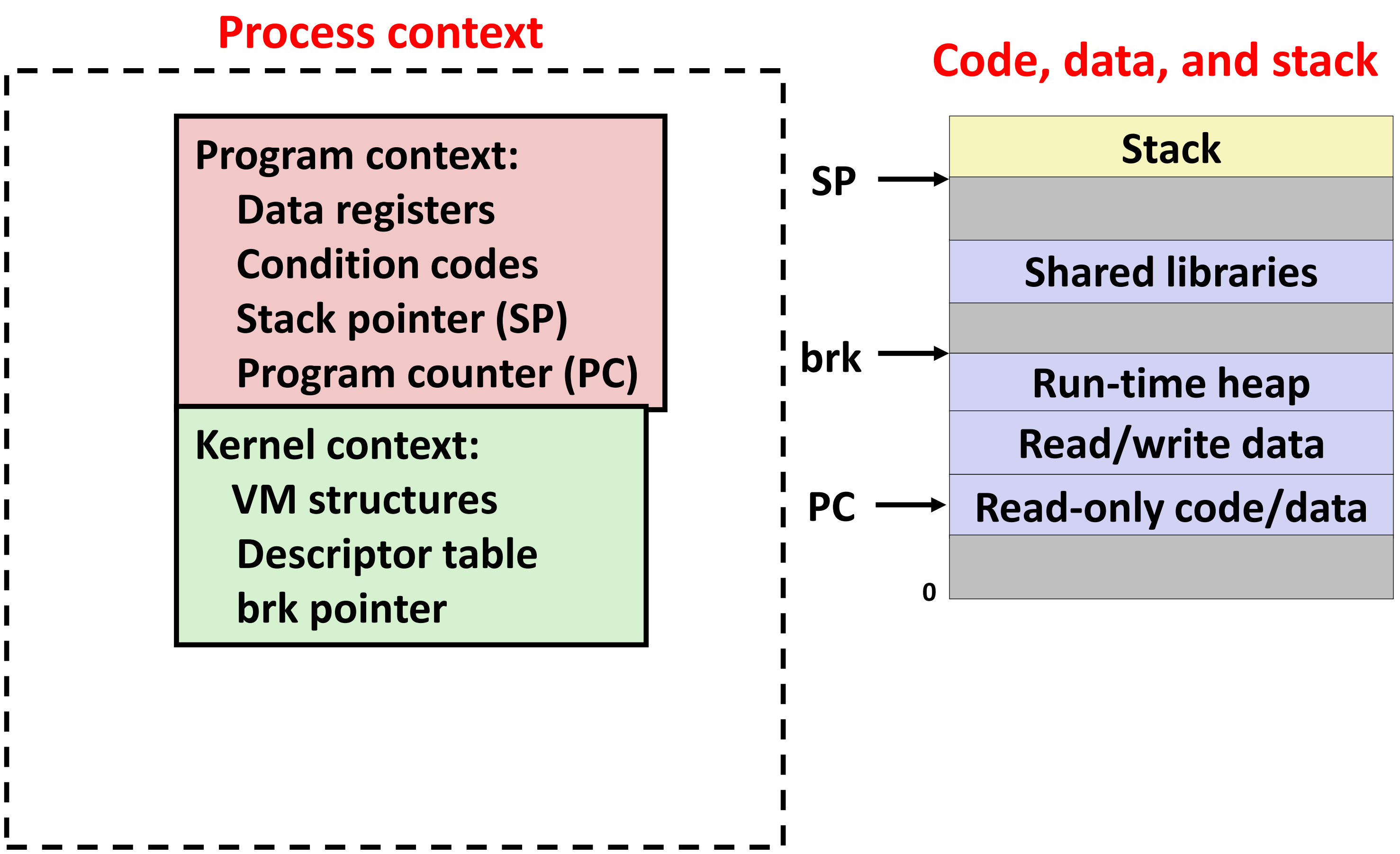
- **– Significantly more complex to code than process- or thread-based designs.**
- **– Hard to provide fine-grained concurrency**
  - E.g., how to deal with partial HTTP request headers
- **– Cannot take advantage of multi-core**
  - Single thread of control

Approach #3: Thread-based Servers

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

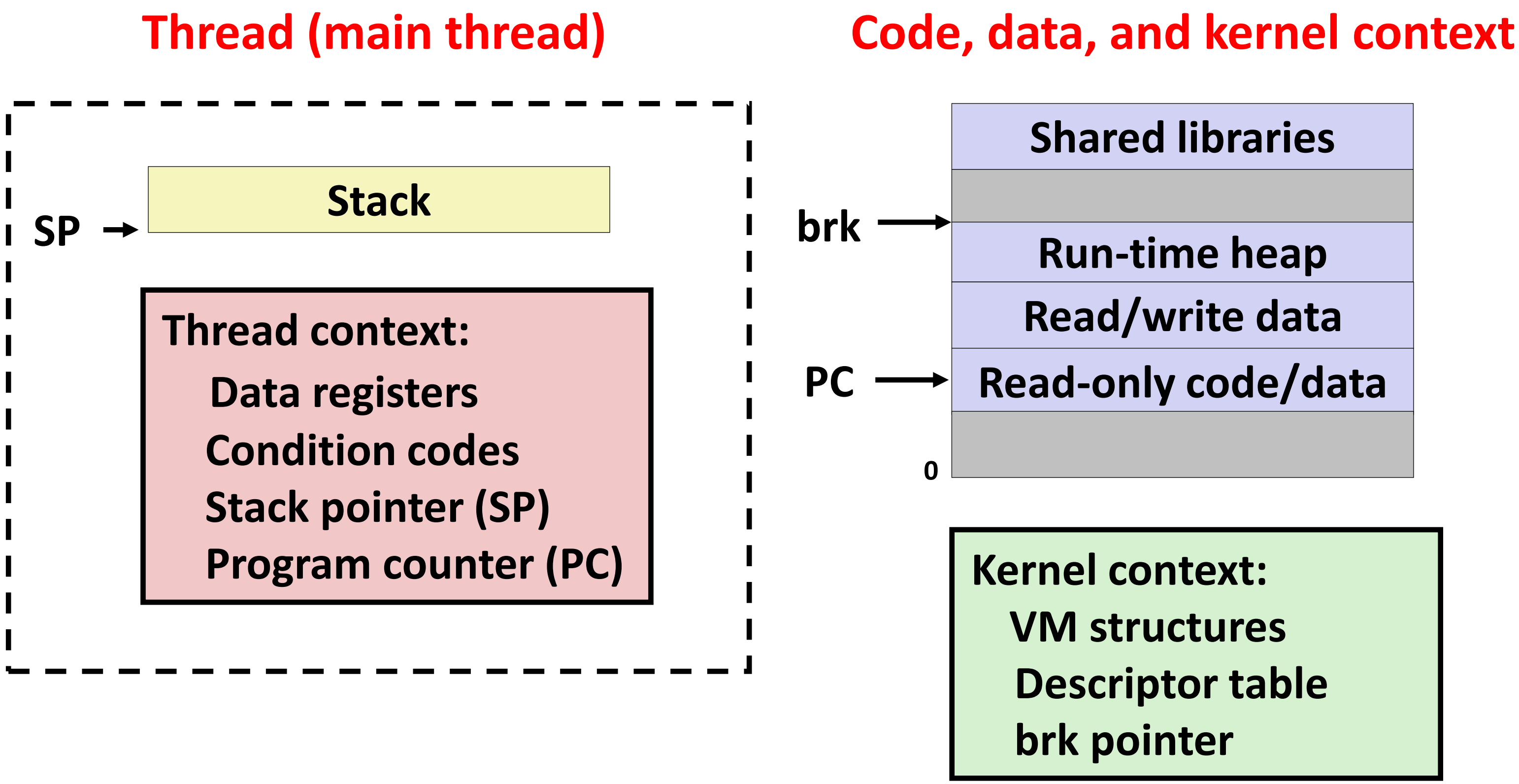
Traditional View of a Process

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



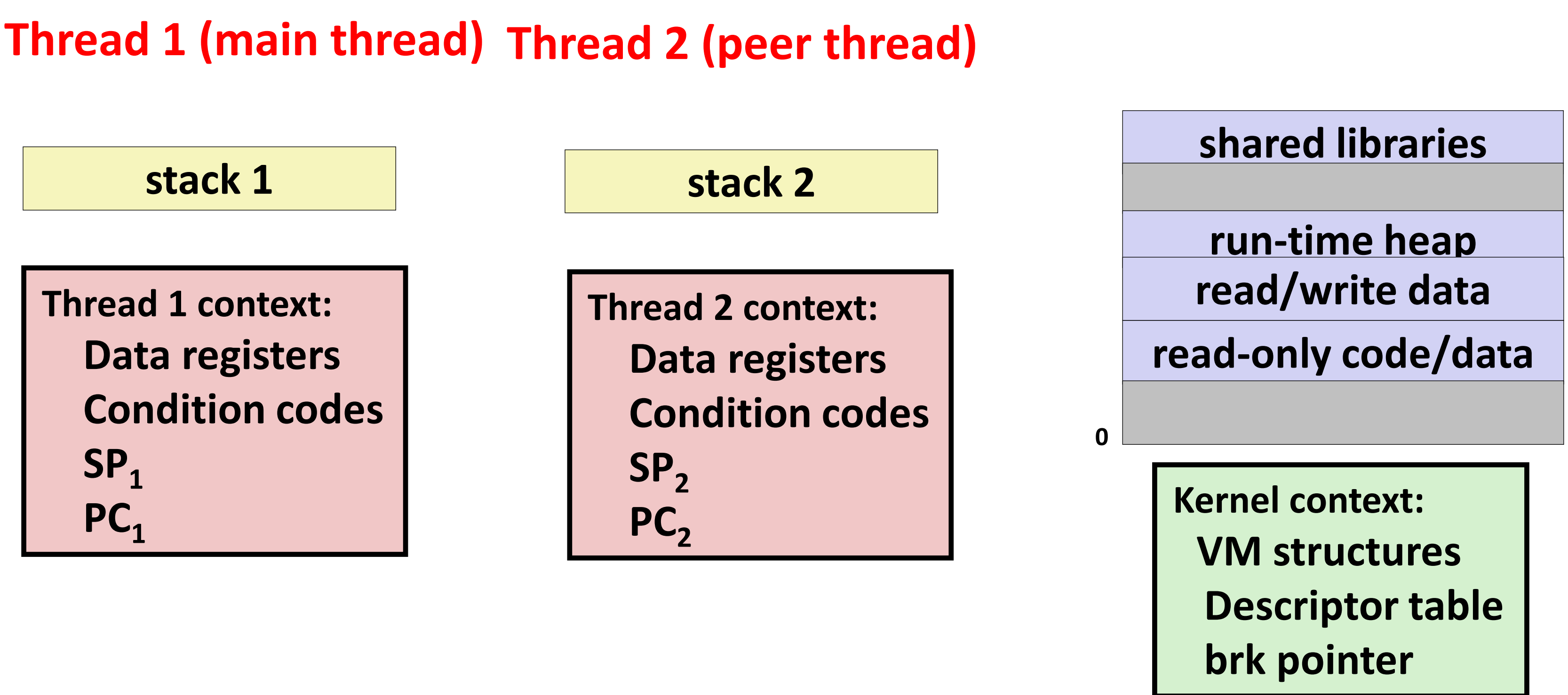
Alternate View of a Process

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



A Process With Multiple Threads

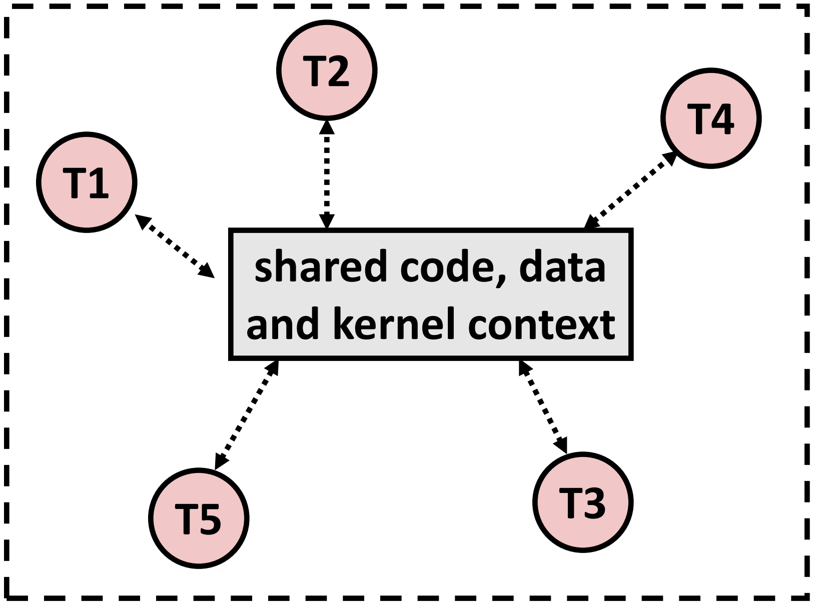
- **Multiple threads can be associated with a process**
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own stack for local variables
    - but not protected from other threads
  - Each thread has its own thread id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



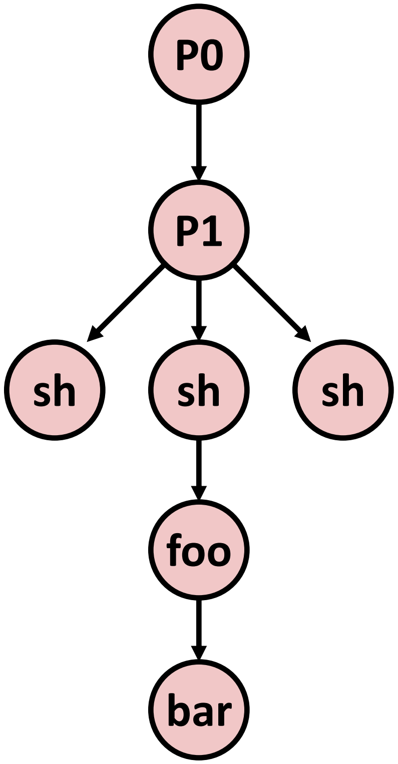
Logical View of Threads

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

Threads associated with process foo

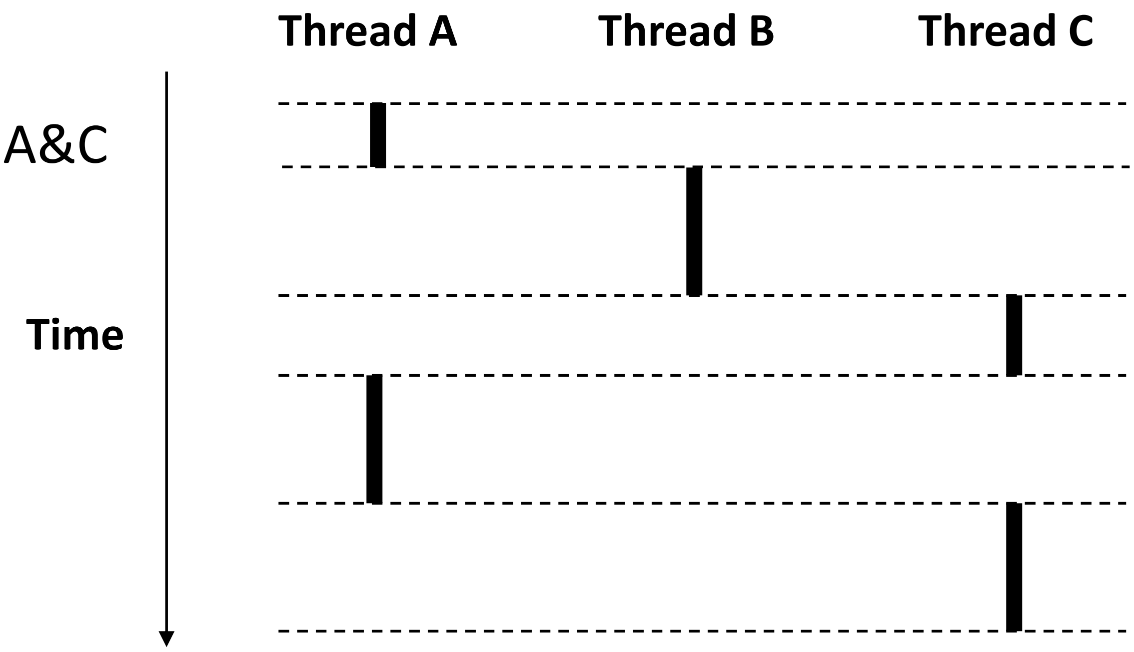


Process hierarchy



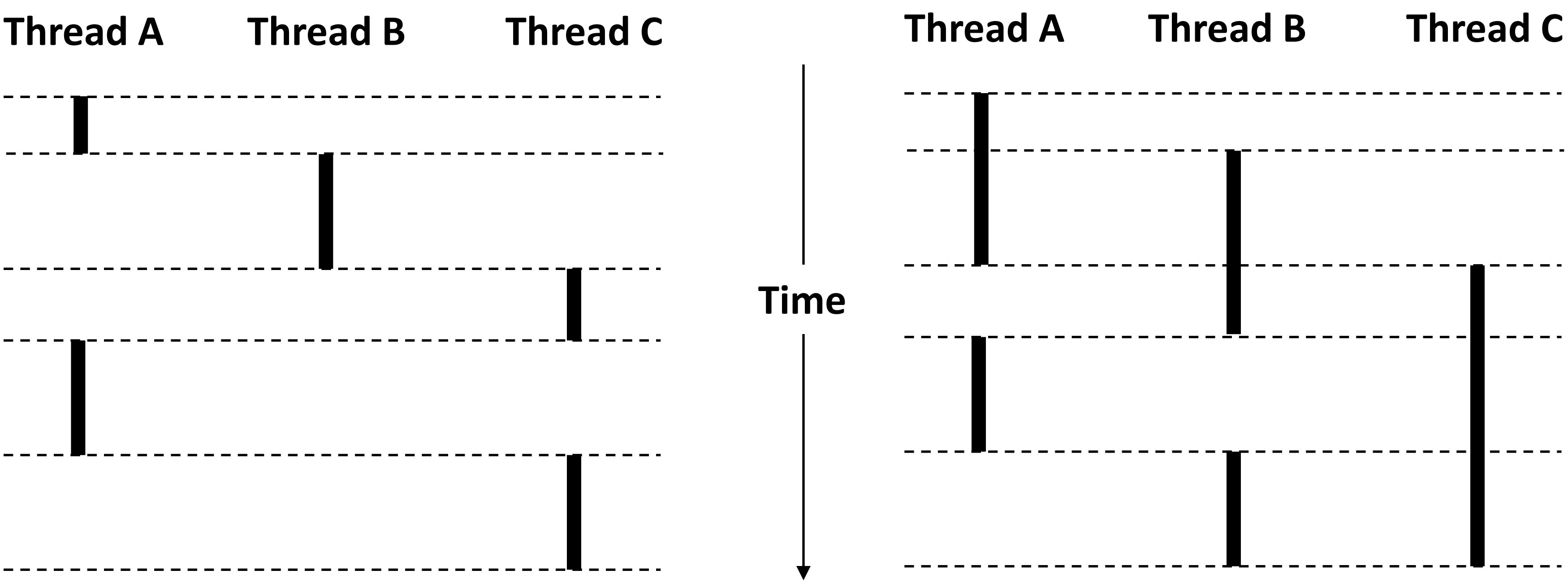
Concurrent Threads

- Two threads are *concurrent* if their flows overlap in time
- Otherwise, they are sequential
- Examples:
  - Concurrent: A & B, A&C
  - Sequential: B & C



Concurrent Thread Execution

- **Single Core Processor**
  - Simulate parallelism by time slicing
- **Multi-Core Processor**
  - Can have true parallelism

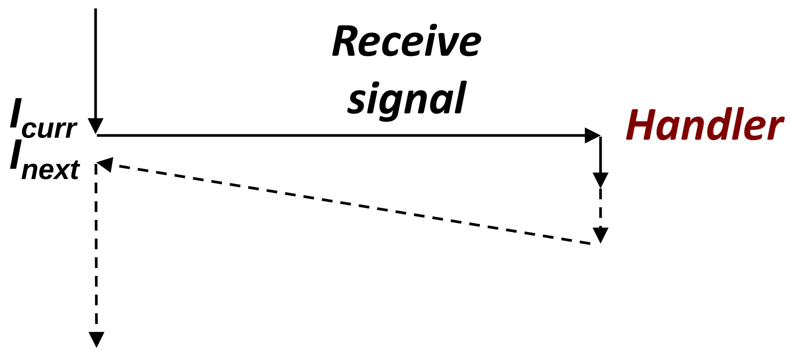


Run 3 threads on 2 cores

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…	
`pthread_create`	`fork`
`pthread_join`	`waitpid`
Determining your ID…	
`pthread_self`	`getpid`
Terminating execution…	
`pthread_exit`	`exit`
`return` from thread proc	`return` from main
Synchronizing operations…	
`pthread_mutex_lock`	[no exact analogue]
`pthread_mutex_unlock`	

The Pthreads "hello, world" Program

```c
/*
 * 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;
}
```

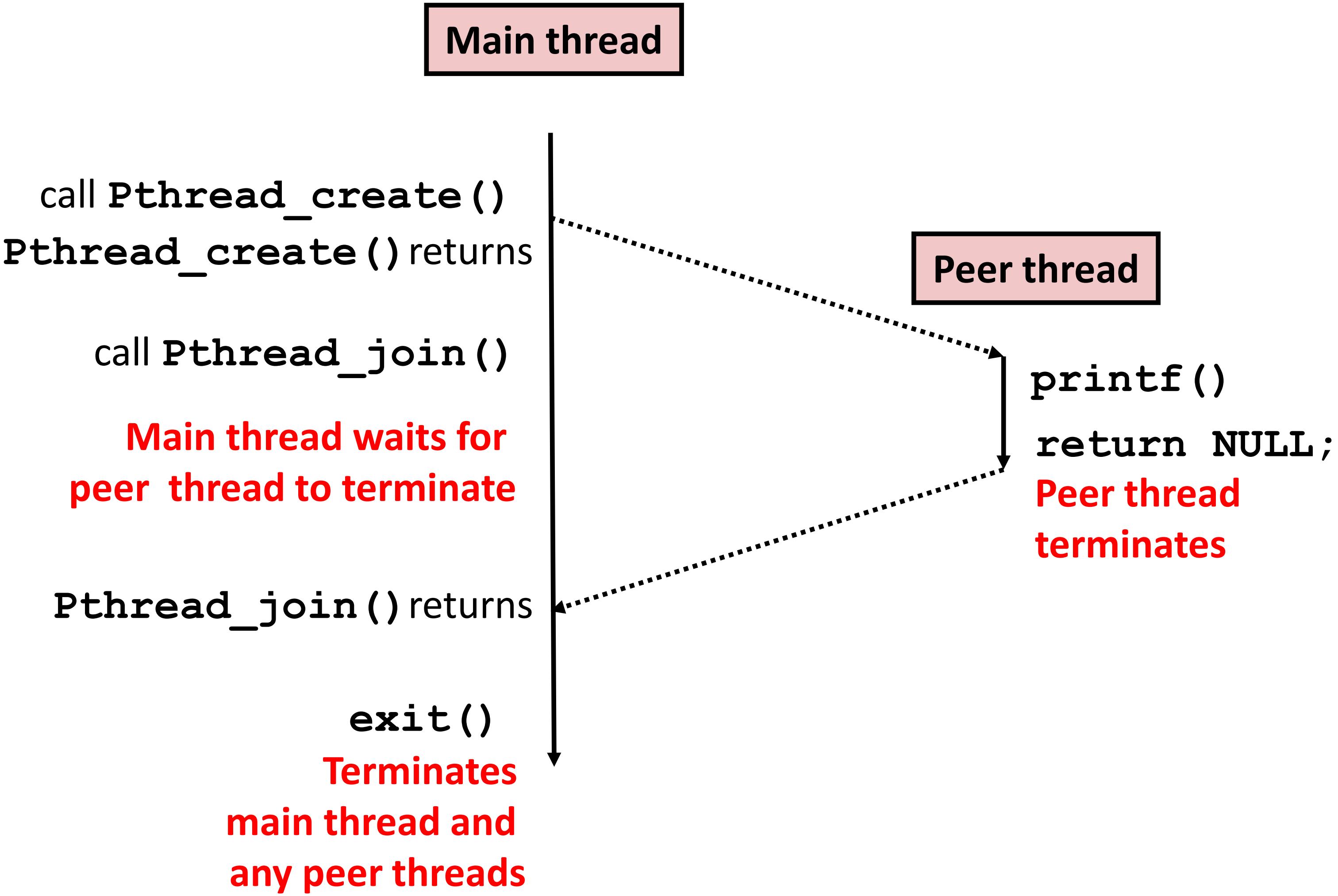
hello.c

- *Thread ID* → &tid
- *Thread attributes (usually NULL)* → first NULL
- *Thread routine* → thread
- *Thread arguments (void *p)* → last NULL in Pthread_create
- *Return value (void **p)* → NULL in Pthread_join

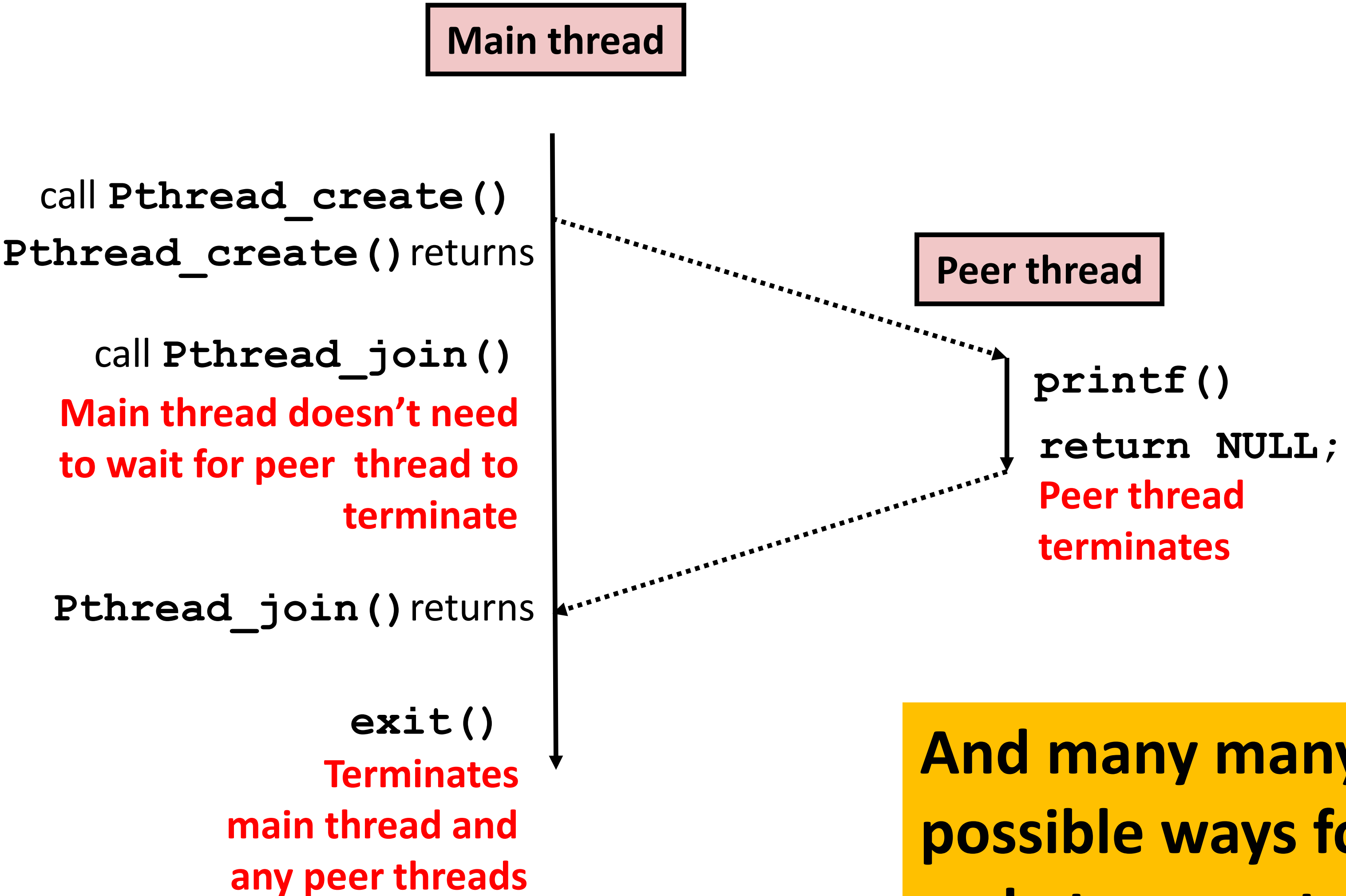
```c
void *thread(void *vargp) /* thread routine */
{
    printf("Hello, world!\n");
    return NULL;
}
```

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;
}
```

echoservert.c

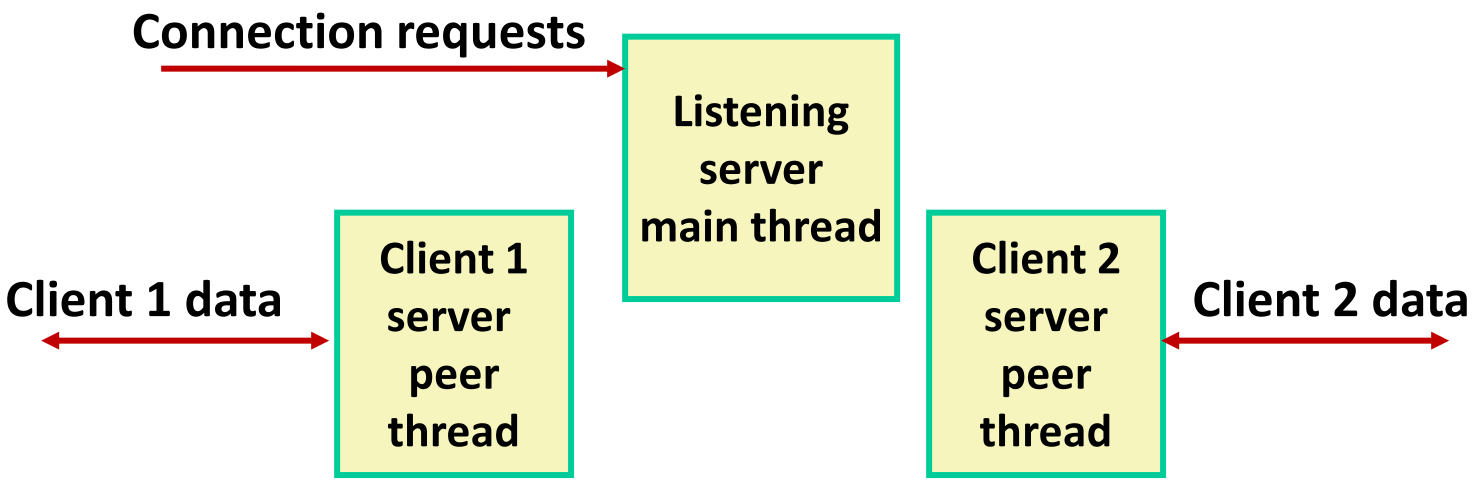
- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of **`Malloc()`**! [but not **`Free()`**]

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;
}
```
echoservert.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



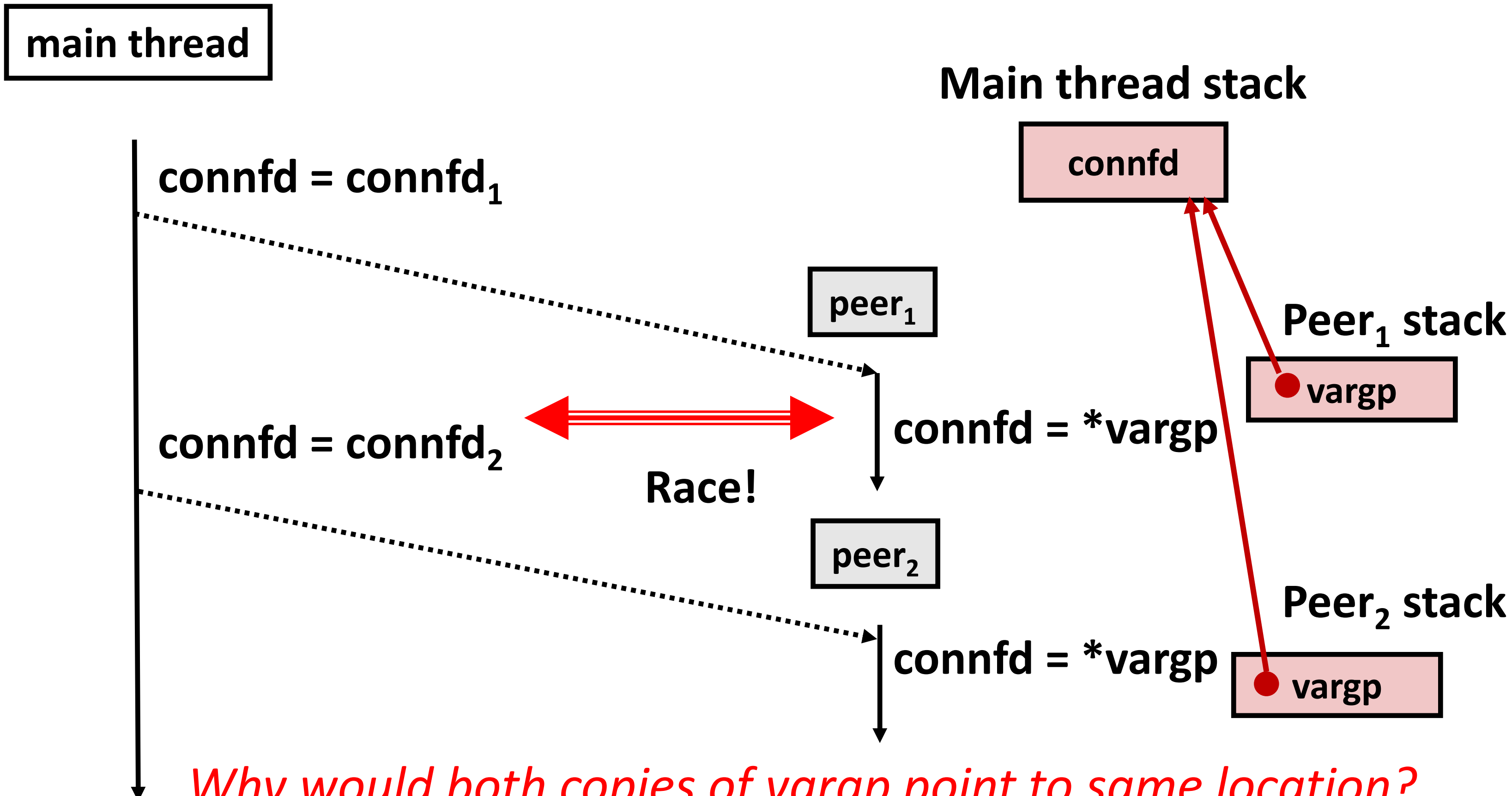
- Each client handled by individual peer thread
- Threads share all process state except TID
- Each thread has a separate stack for local variables

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

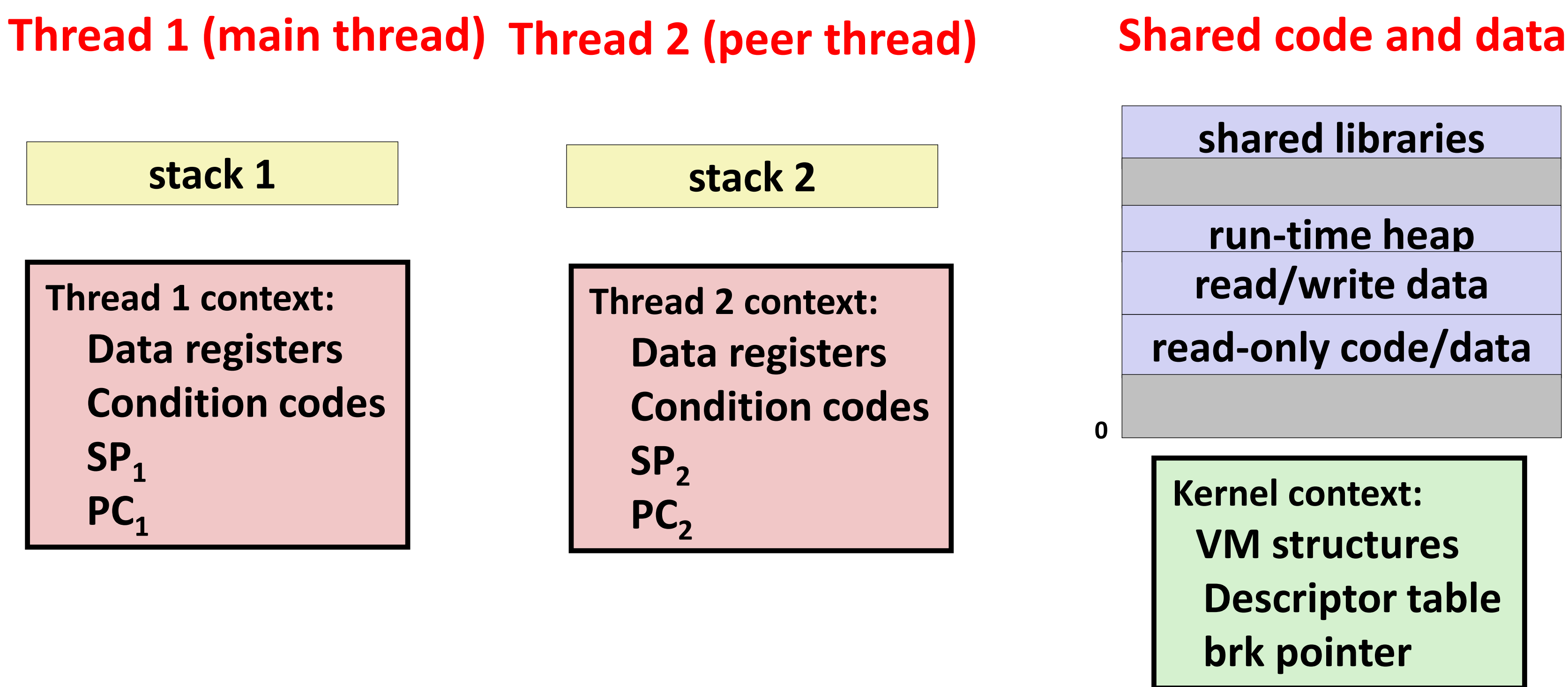
```
while (1) {
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
    Pthread_create(&tid, NULL, thread, &connfd);
}
```



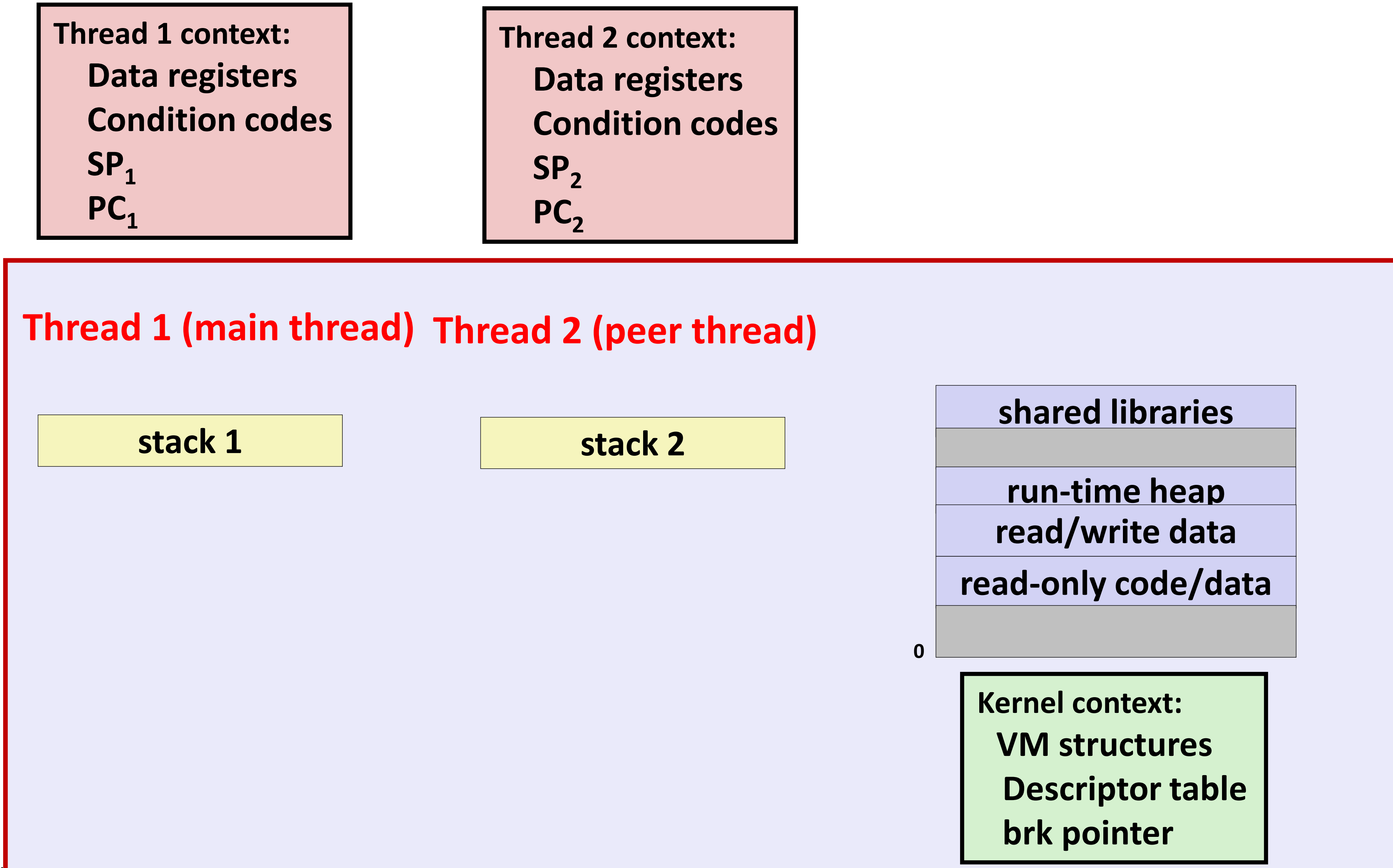
Why would both copies of vargp point to same location?

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)



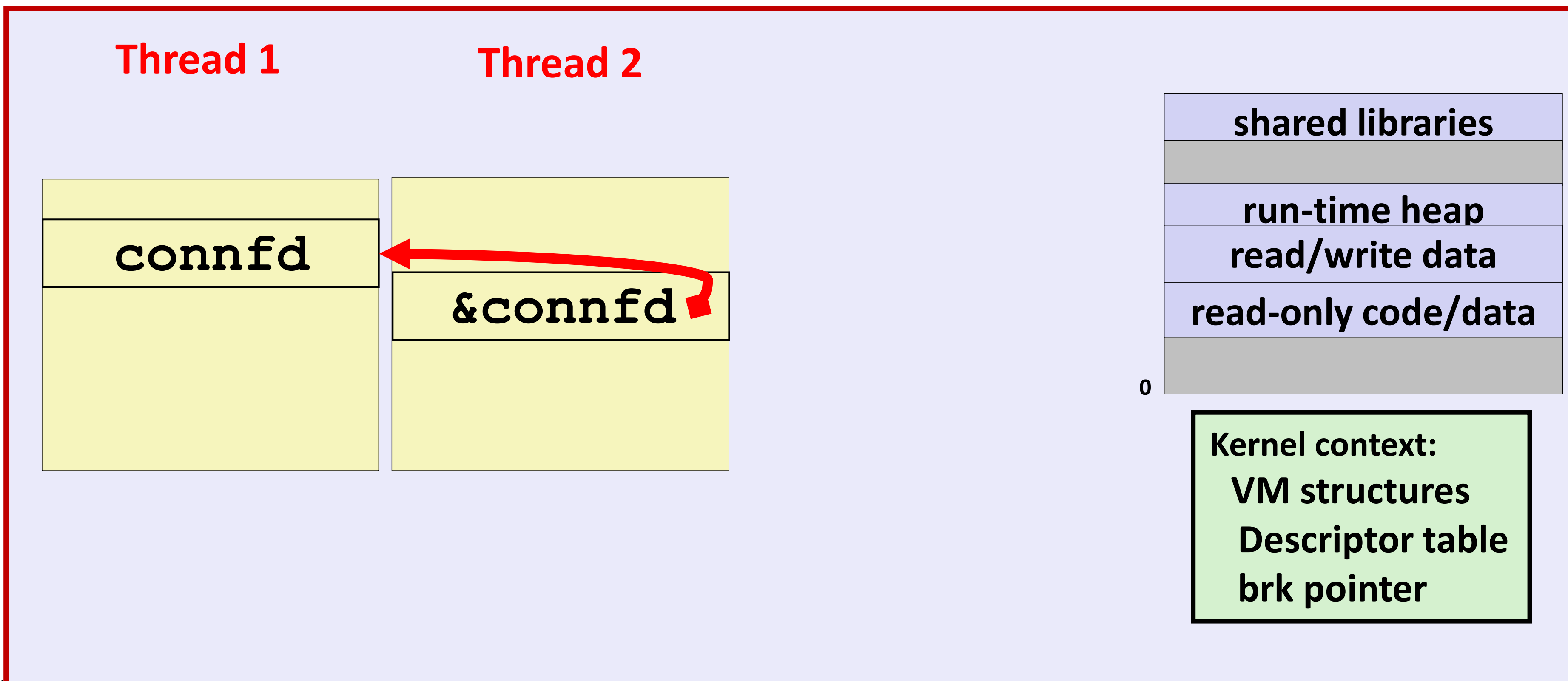
But ALL memory is shared



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

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

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

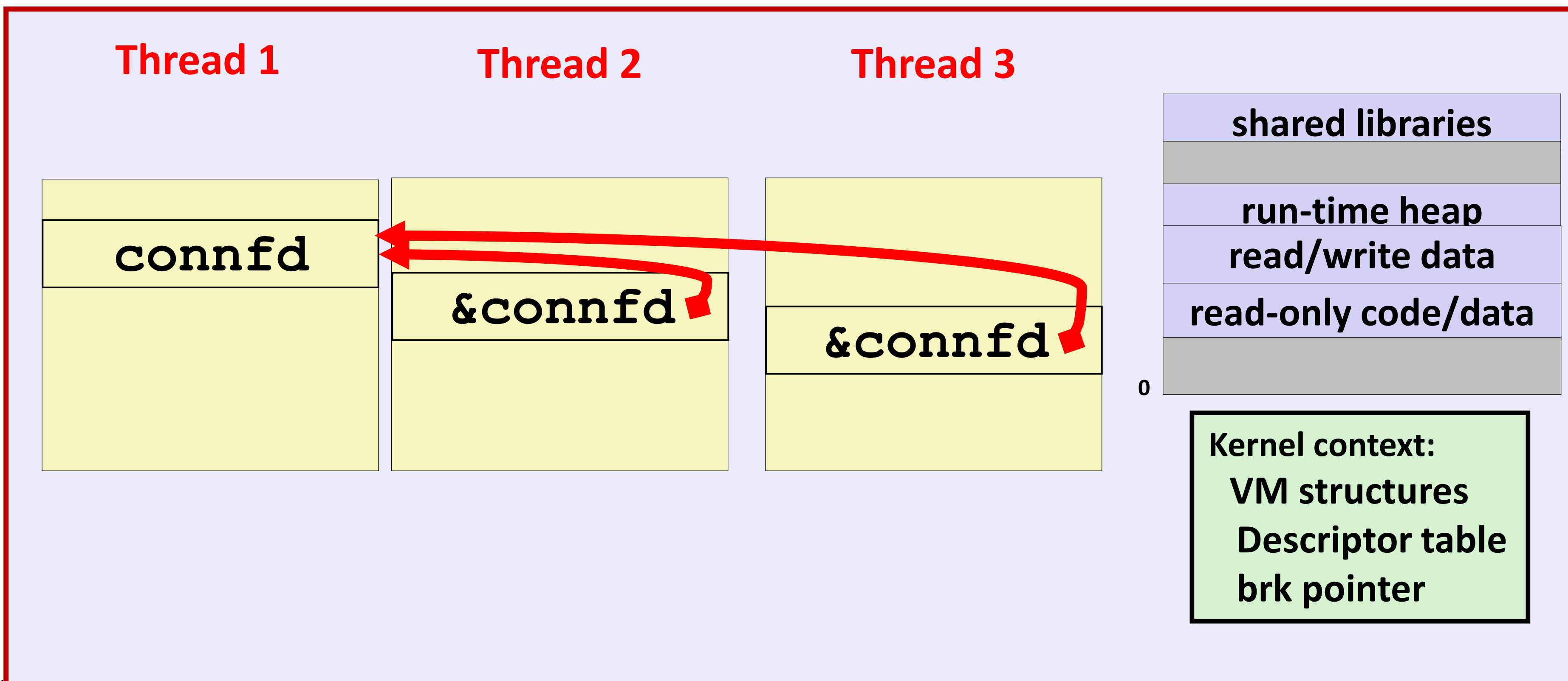


```
while (1) {
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
    Pthread_create(&tid, NULL, thread, &connfd);
}
```

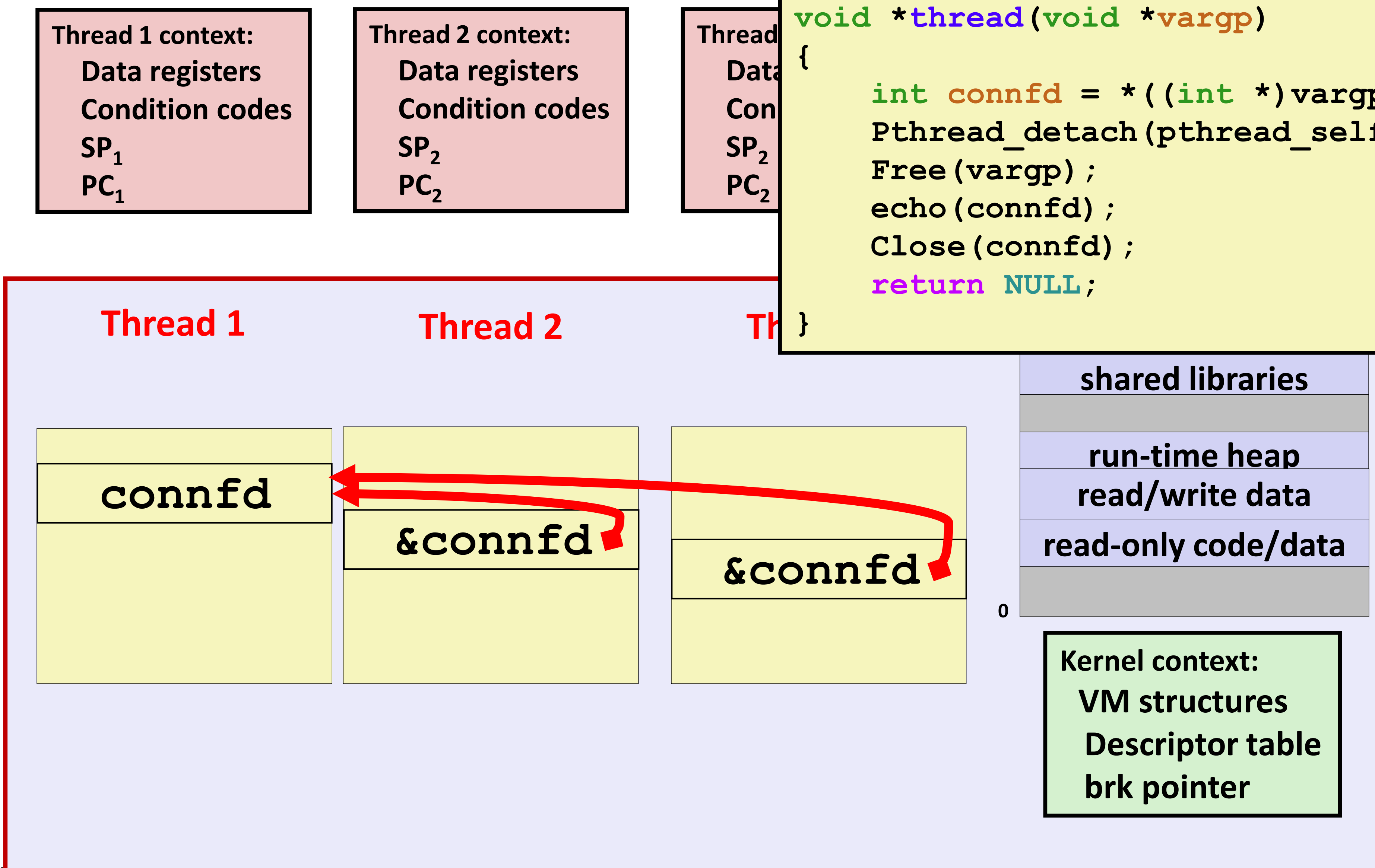
Thread 1 context:
- Data registers
- Condition codes
- SP_1
- PC_1

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

Thread 3 context:
- Data registers
- Condition codes
- 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;
}
```



Could this race occur?

Main

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

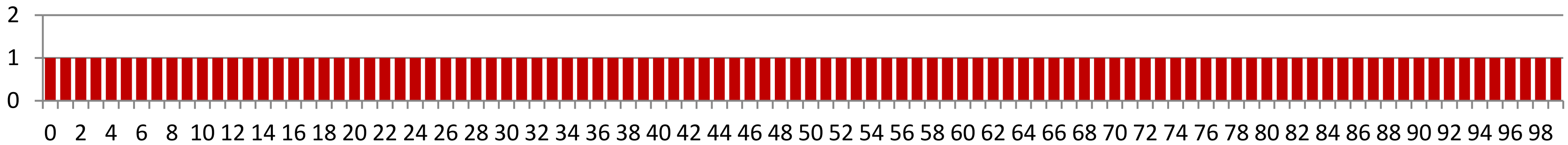
Thread

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

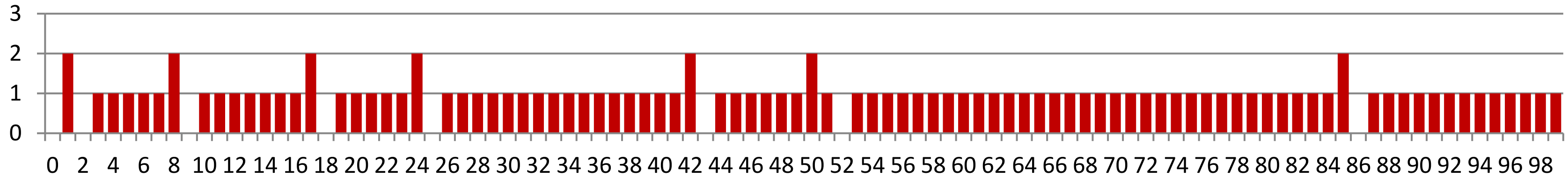
- **Race Test**
  - If no race, then each thread would get different value of `i`
  - Set of saved values would consist of one copy each of 0 through 99

Experimental Results

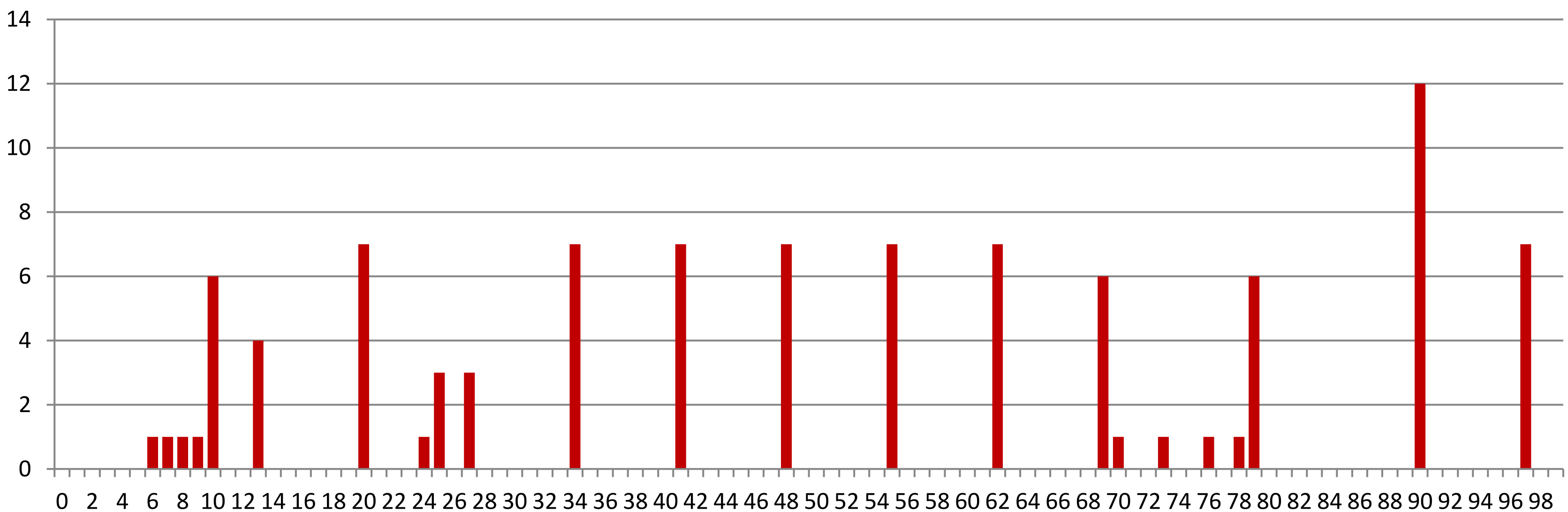
No Race



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