Concurrent Programming

Introduction to Computer Systems
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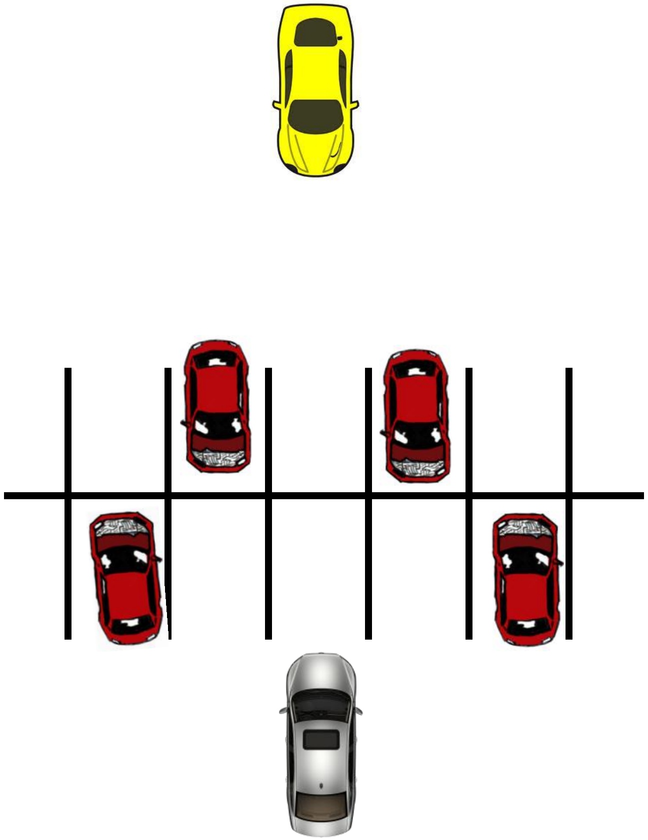
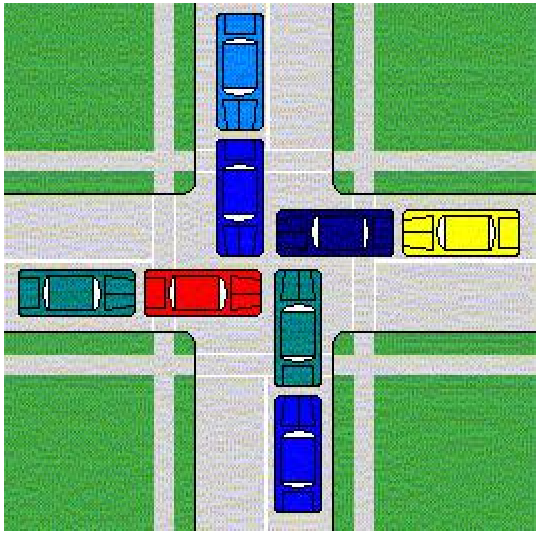
Concurrent Programming is Hard!

- 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

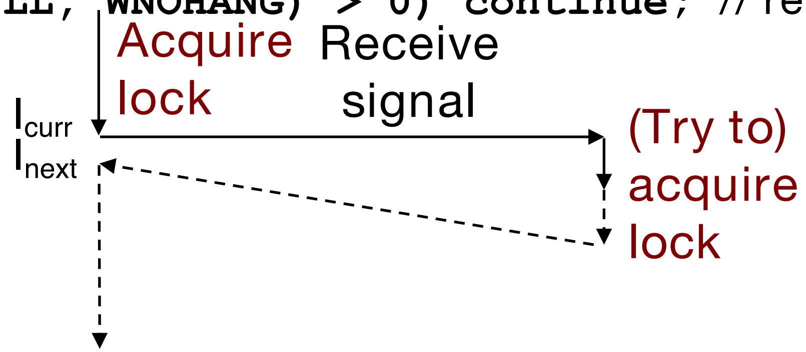


Deadlock

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

```
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



- What if signal handler interrupts call to printf?

Testing Printf Deadlock

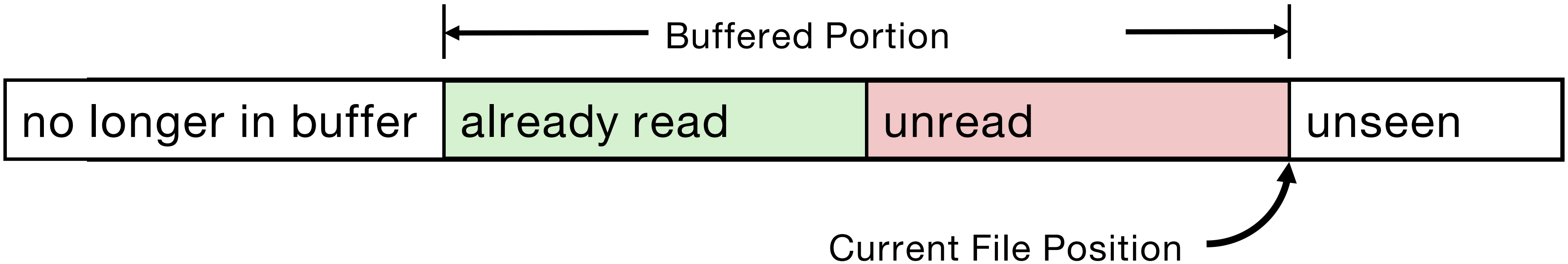
```
void catch_child(int signo) {
   printf("Child exited!\n"); // this call may reenter printf/puts! BAD! DEADLOCK!
   while (waitpid(-1, NULL, WNOHANG) > 0) continue; // reap all children
}

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;
}
```

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

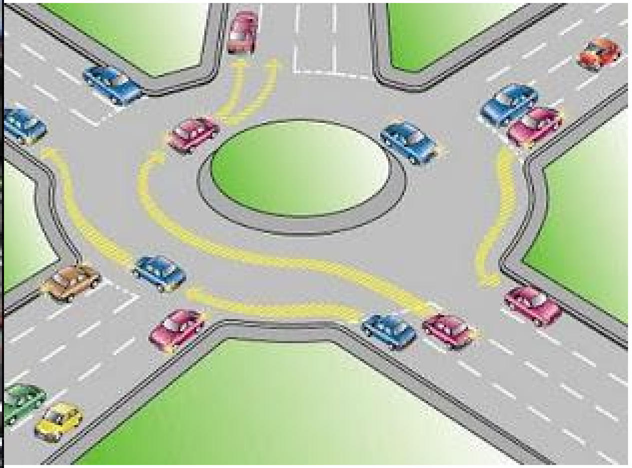
Why Does Printf require Locks?

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

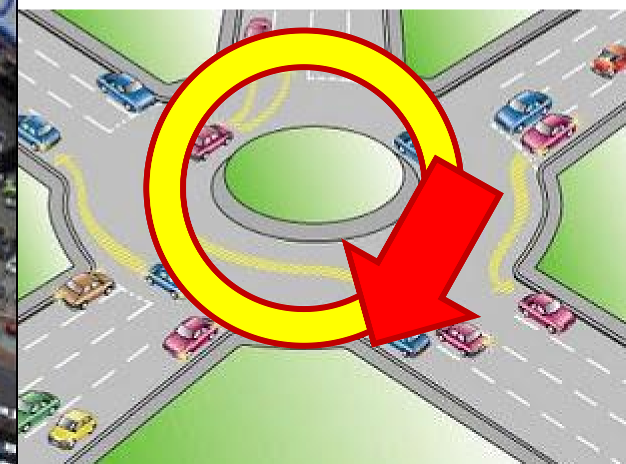


- Require locks to access to shared buffers

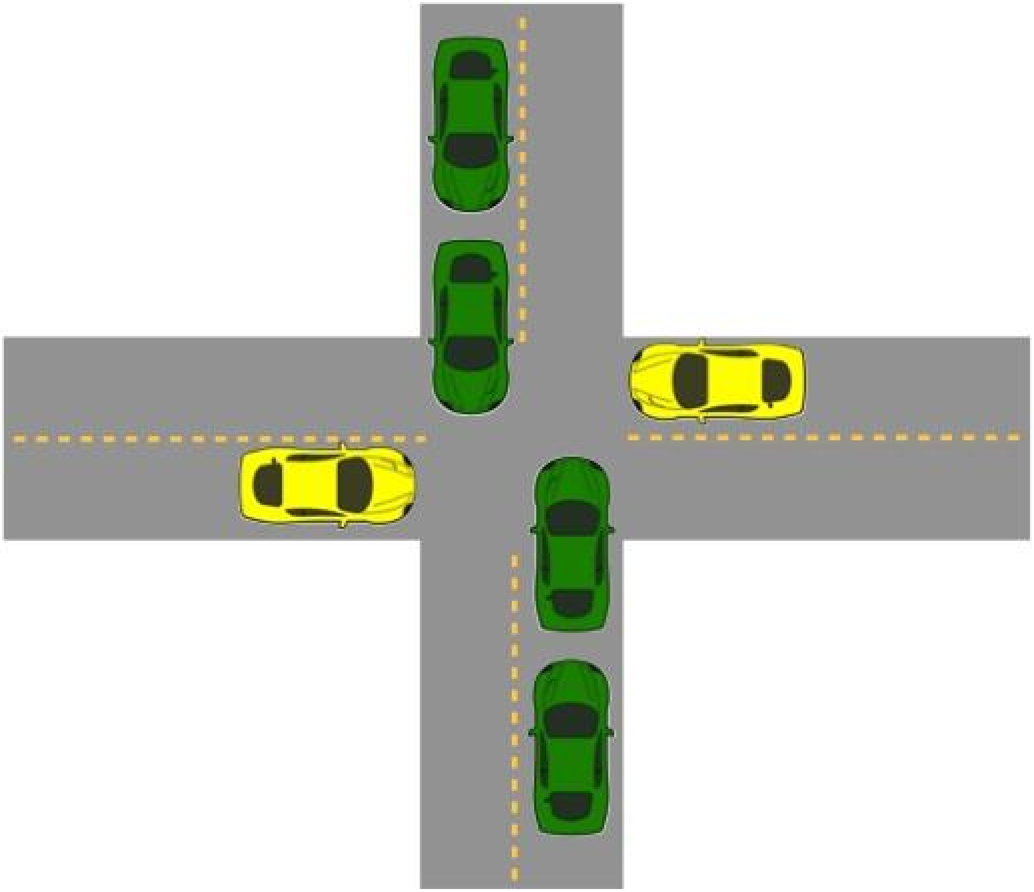
Livelock



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
  - 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 ☺

Concurrent Programming is Hard!

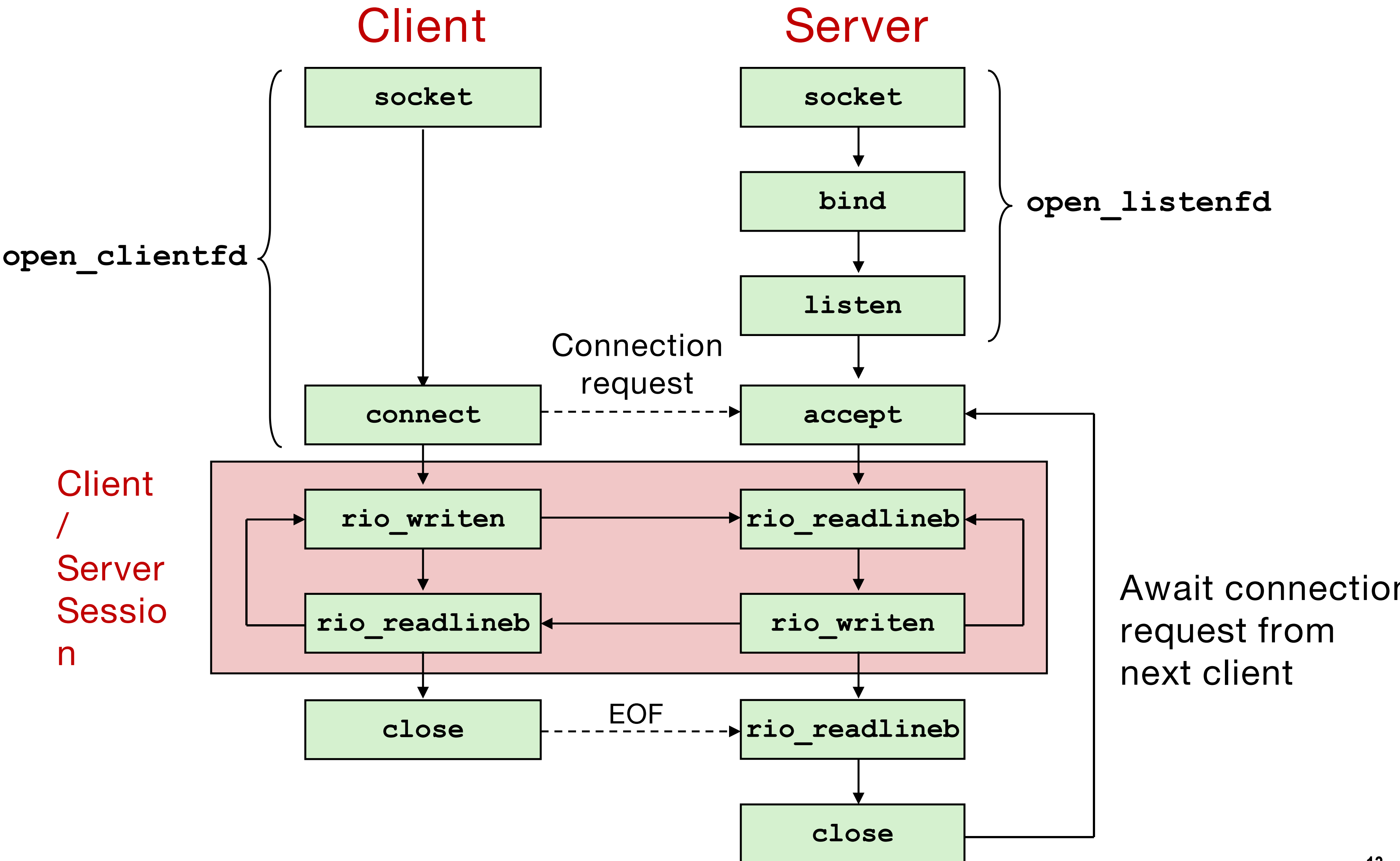
It may be hard, but …

it can be useful and

more and more necessa

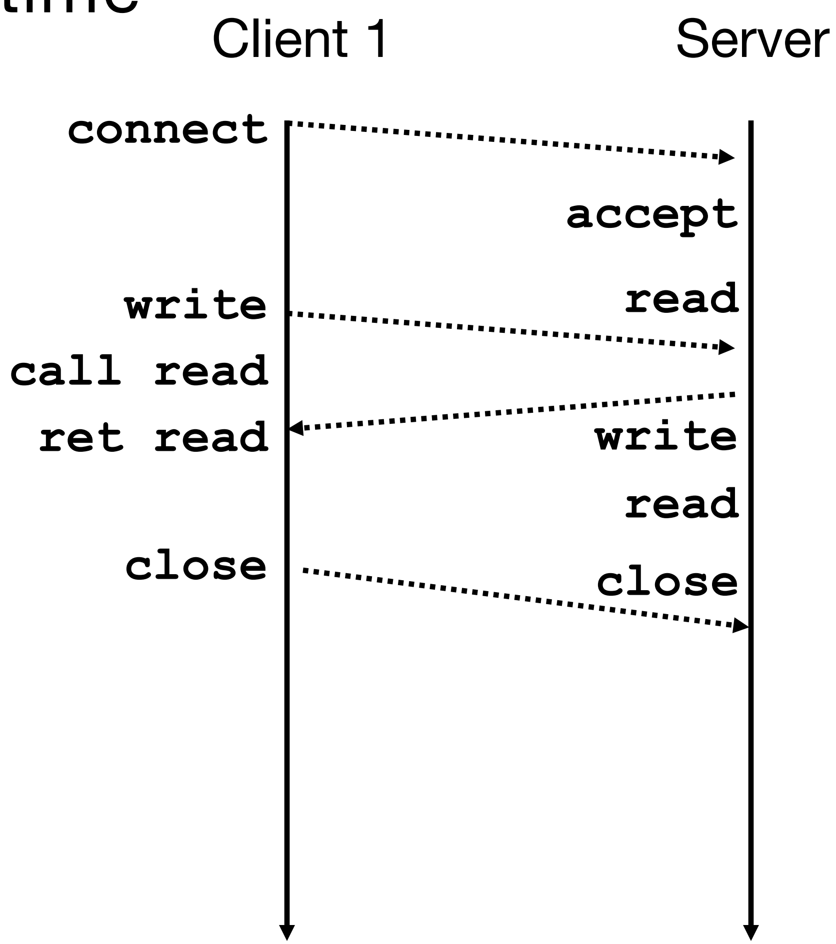
necessary!

Reminder: Iterative Echo Server



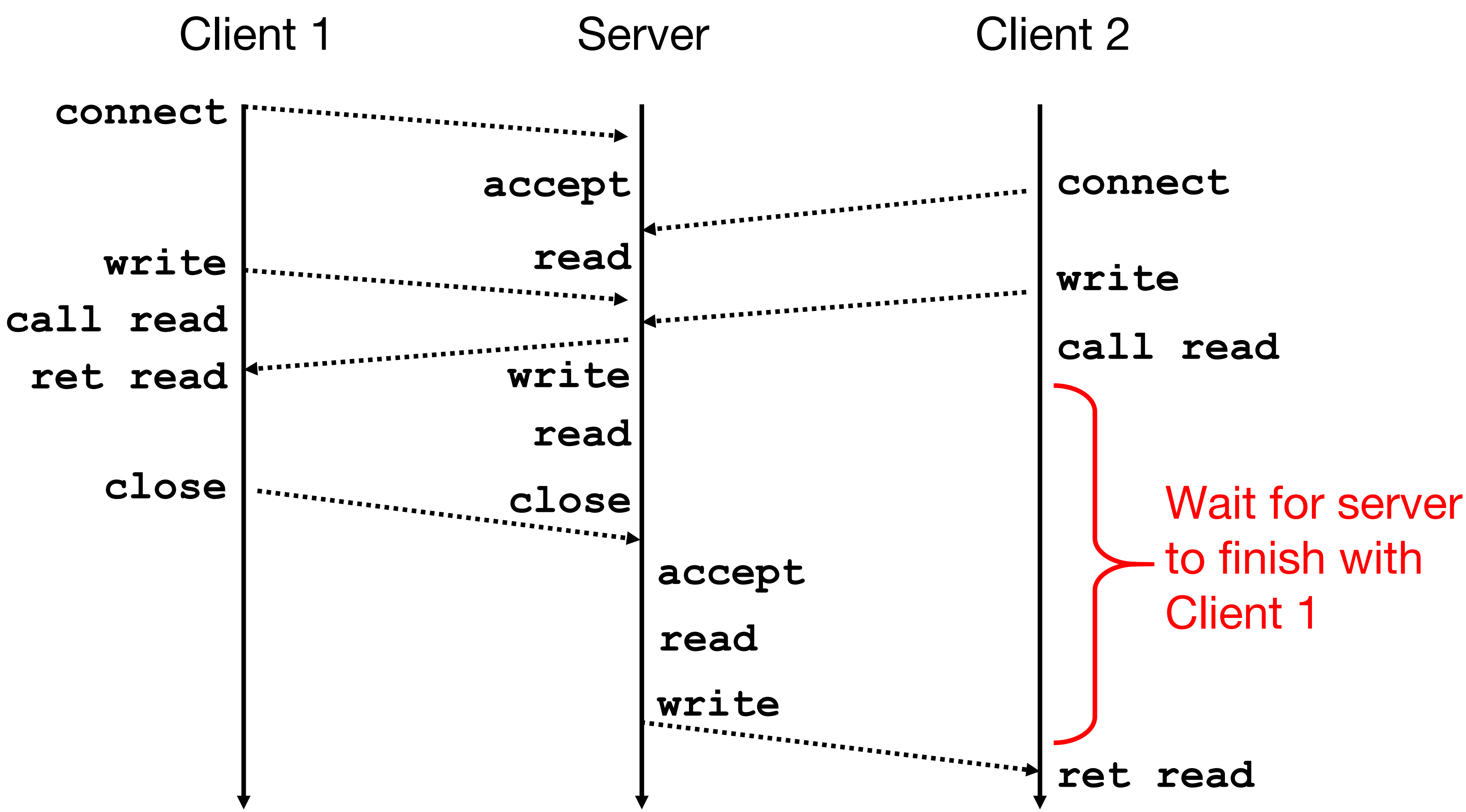
Iterative Servers

- Iterative servers process one connection at a time



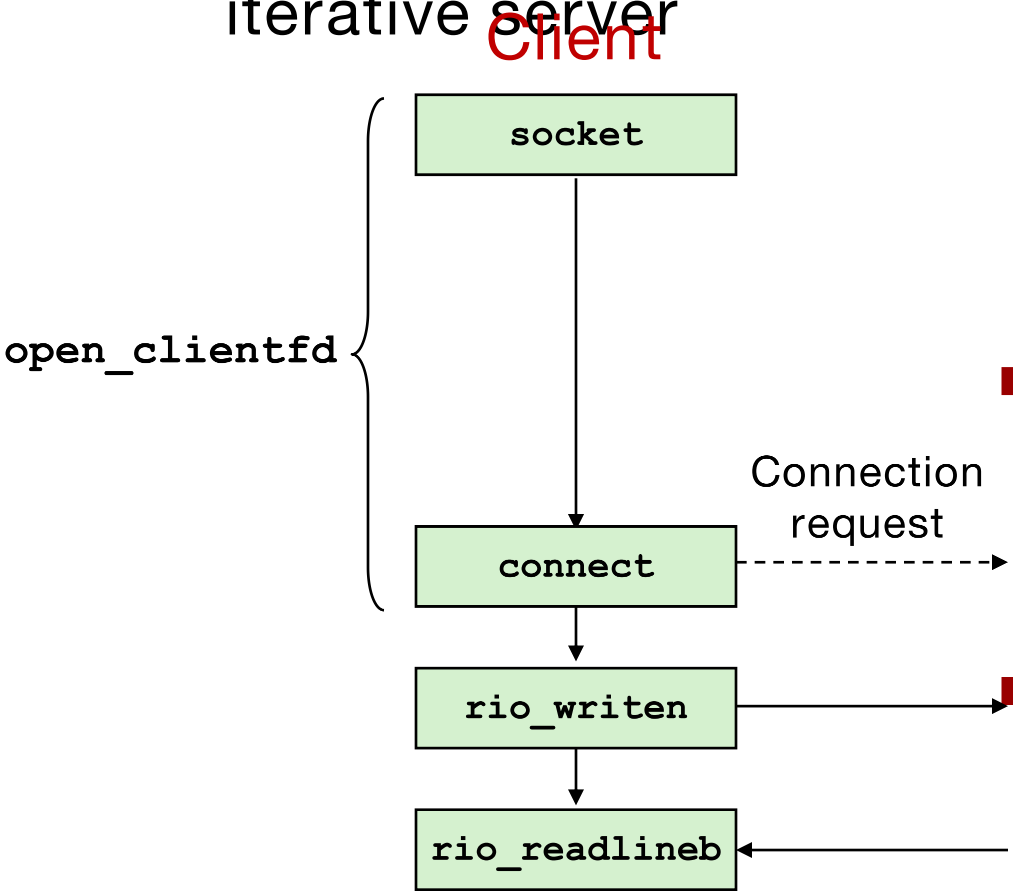
Iterative Servers

- Iterative servers process one request at a time



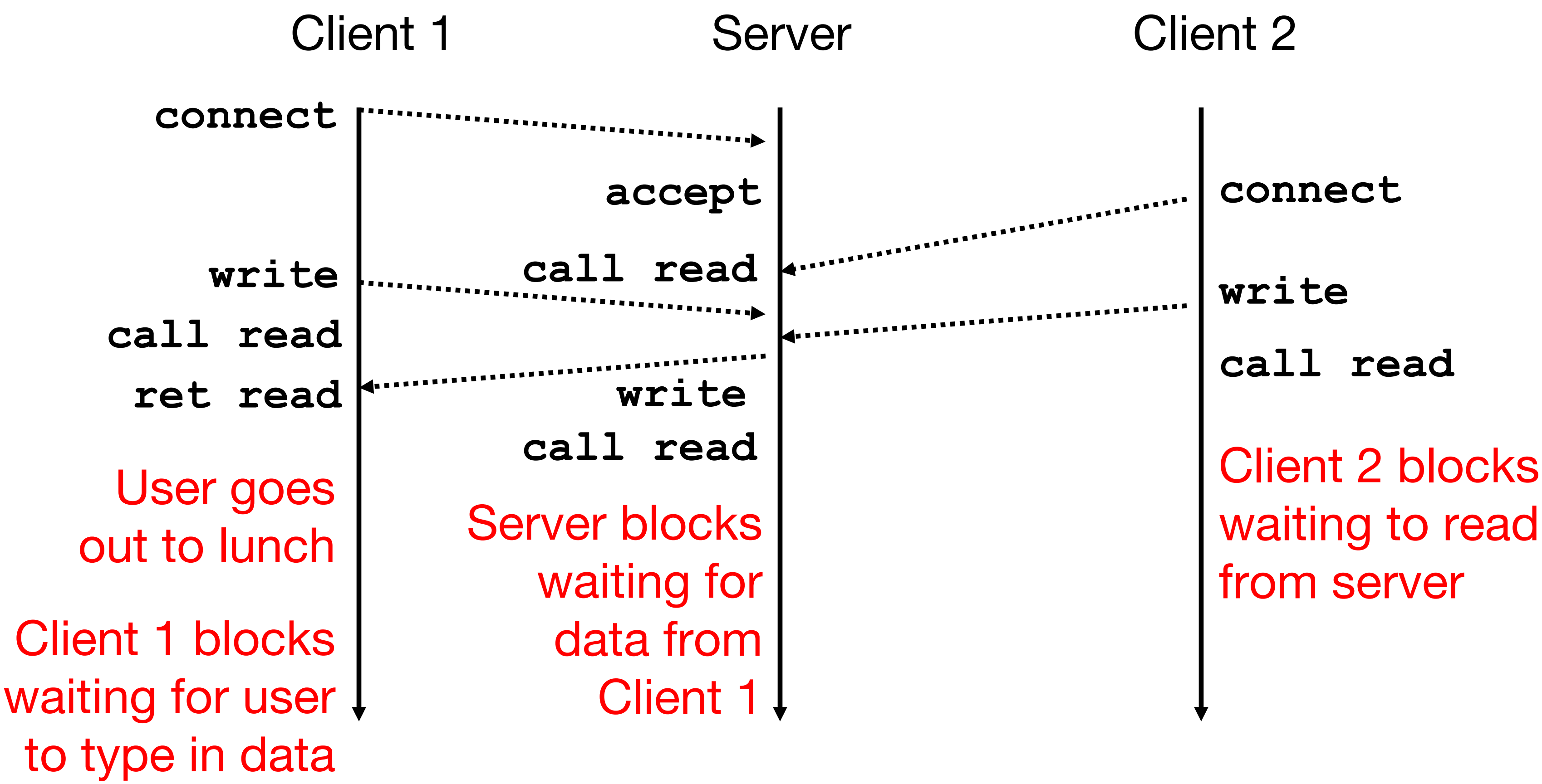
Where Does Second Client Block?

- 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

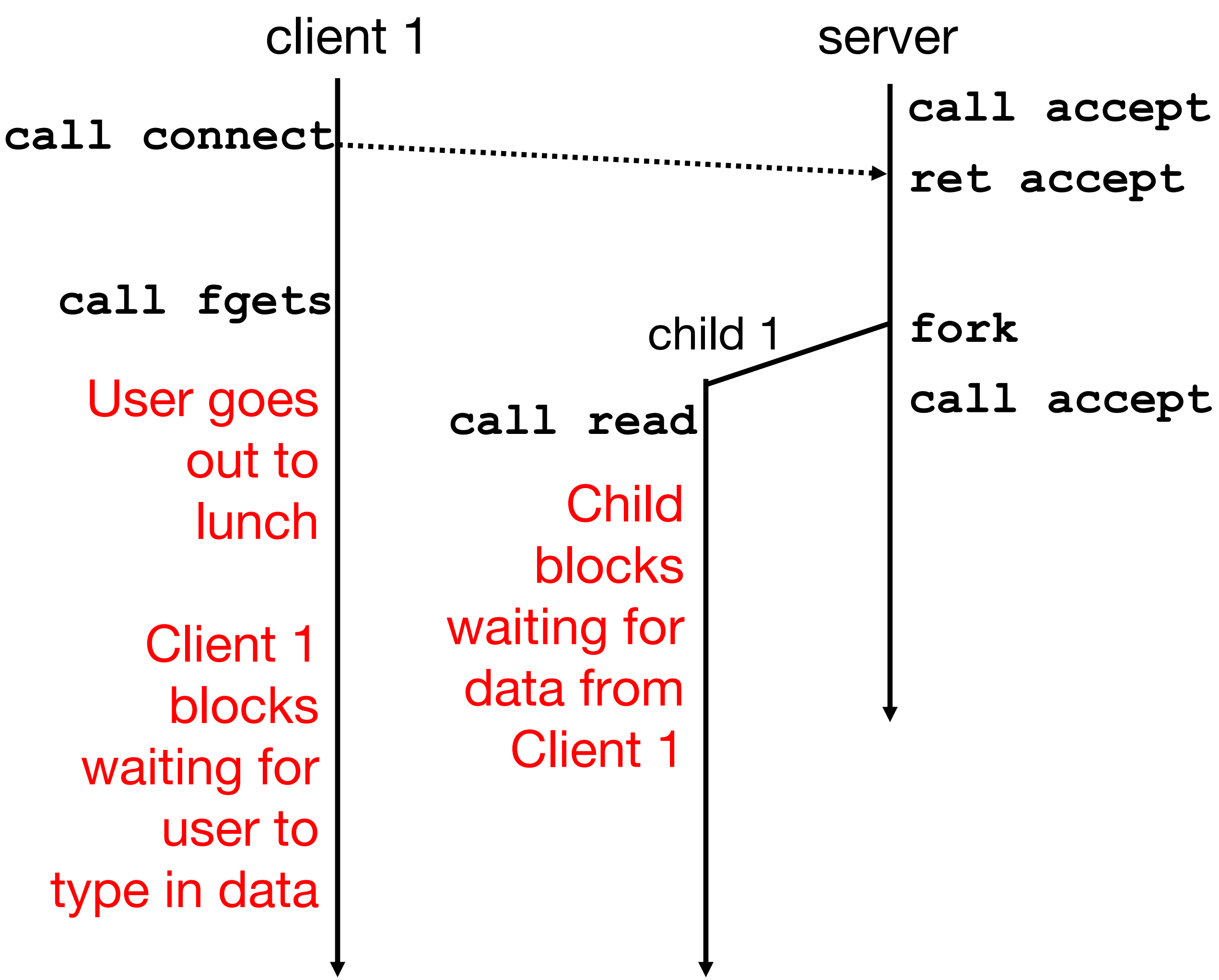
Approaches for Writing Concurrent Servers

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.

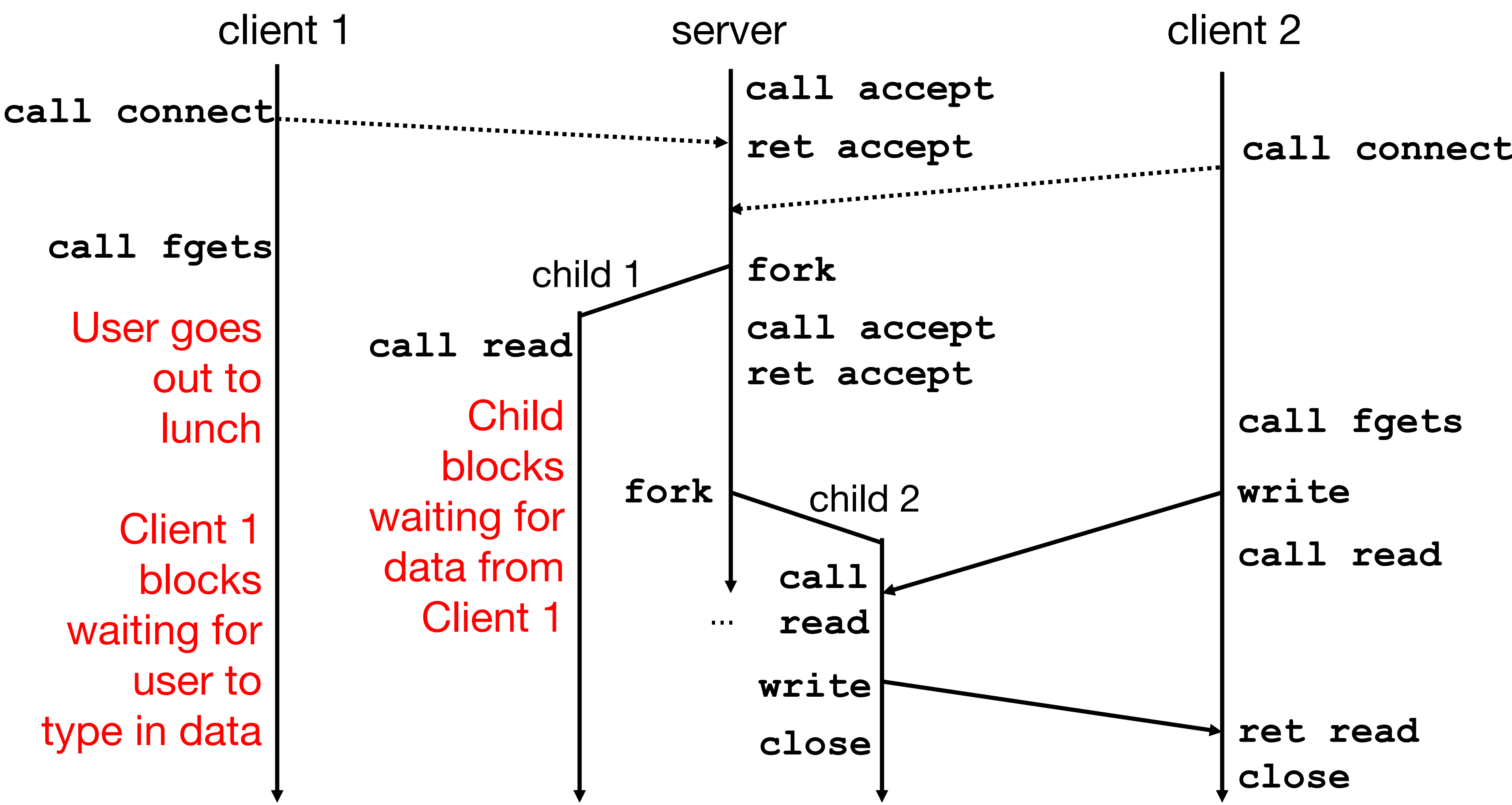
Approach #1: Process-based Servers

- 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

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);



    }
}
```

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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 */
        }

    }
}
```

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

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Why?

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) {
            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!) */
    }
}
```

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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!) */
    }
}
```

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Process-Based Concurrent Echo Server (cont)

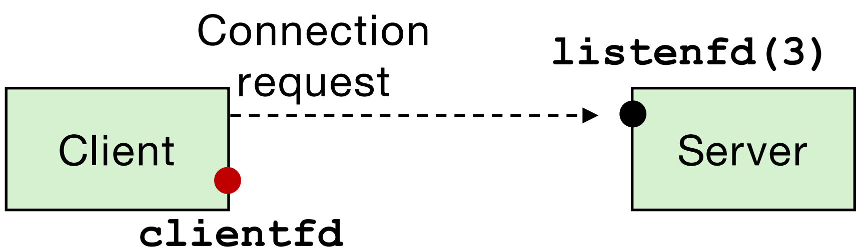
```
void sigchld_handler(int sig)
{
    while (waitpid(-1, 0, WNOHANG) > 0)
        ;
    return;
}
```

echoserverp.c

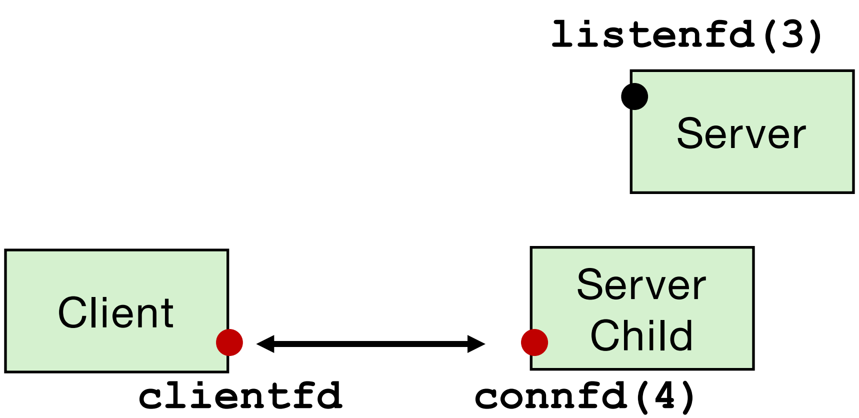
- Reap all zombie children

Concurrent Server: `accept` Illustrated

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

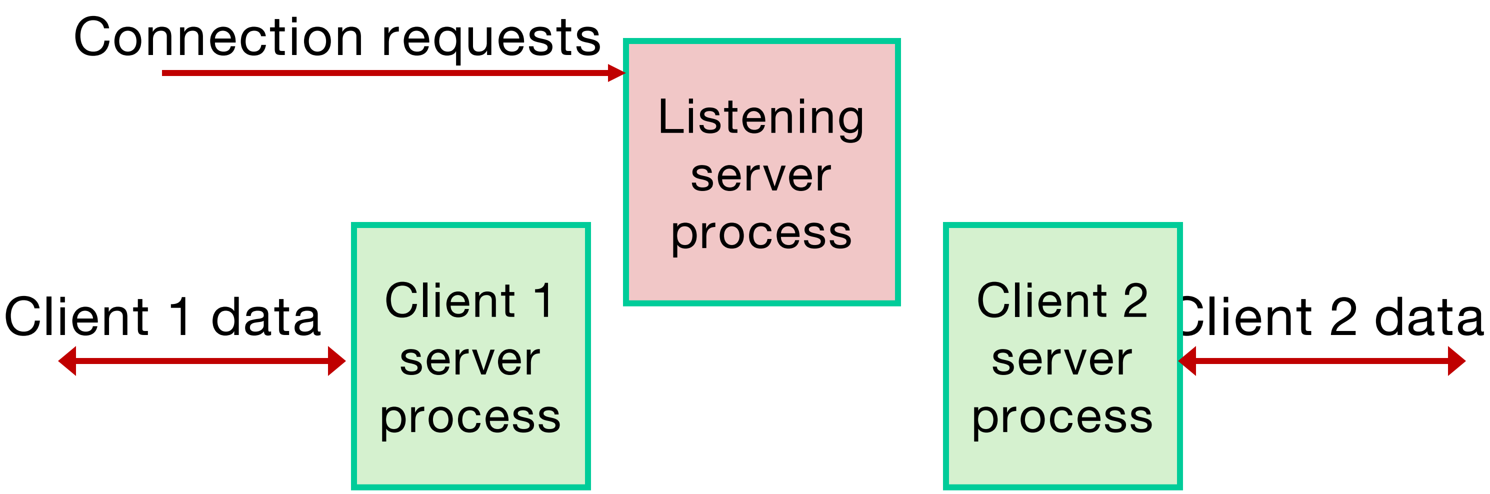


2. Client makes connection request by calling ***connect***



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`

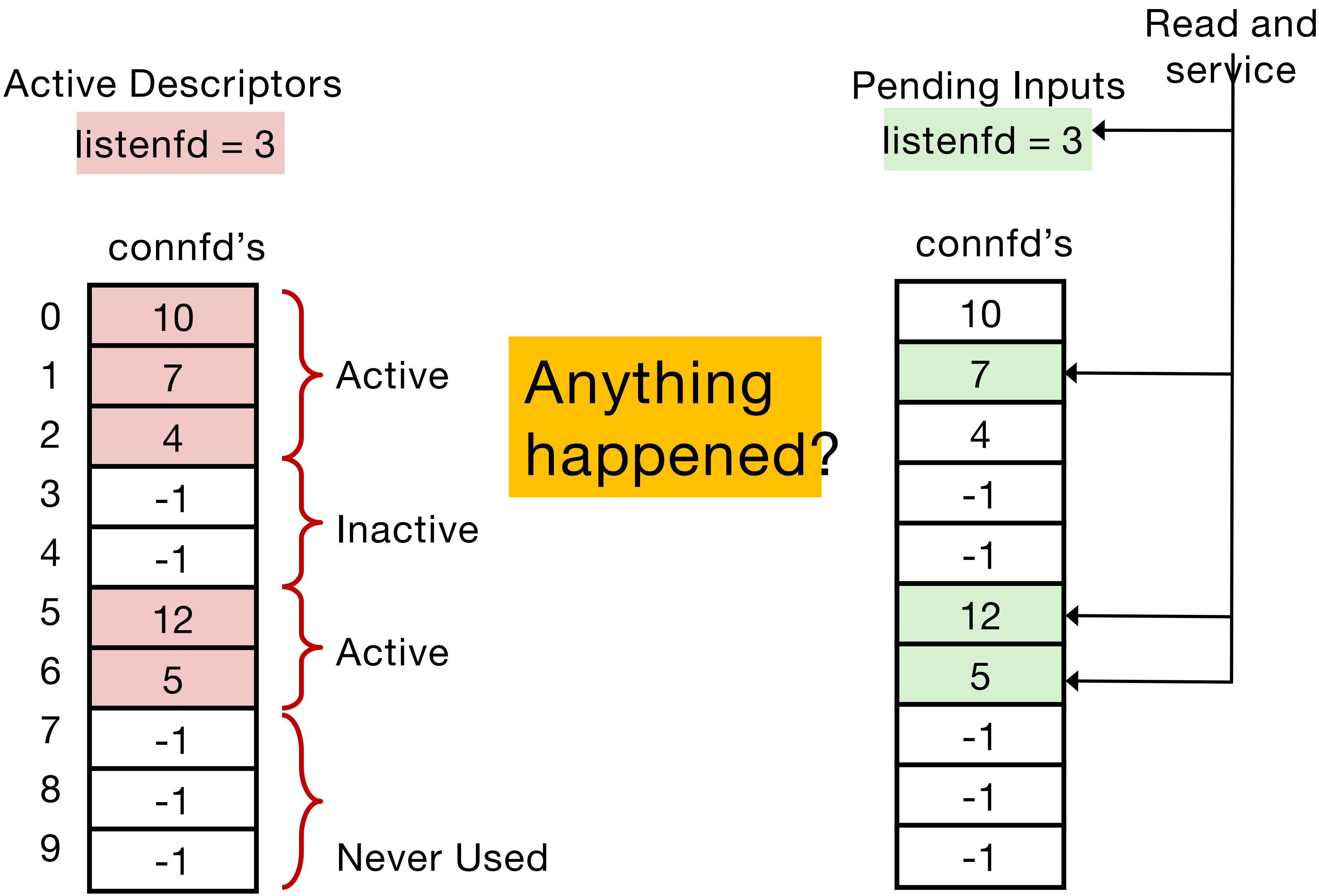
Pros and Cons of Process-based Servers

- + 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

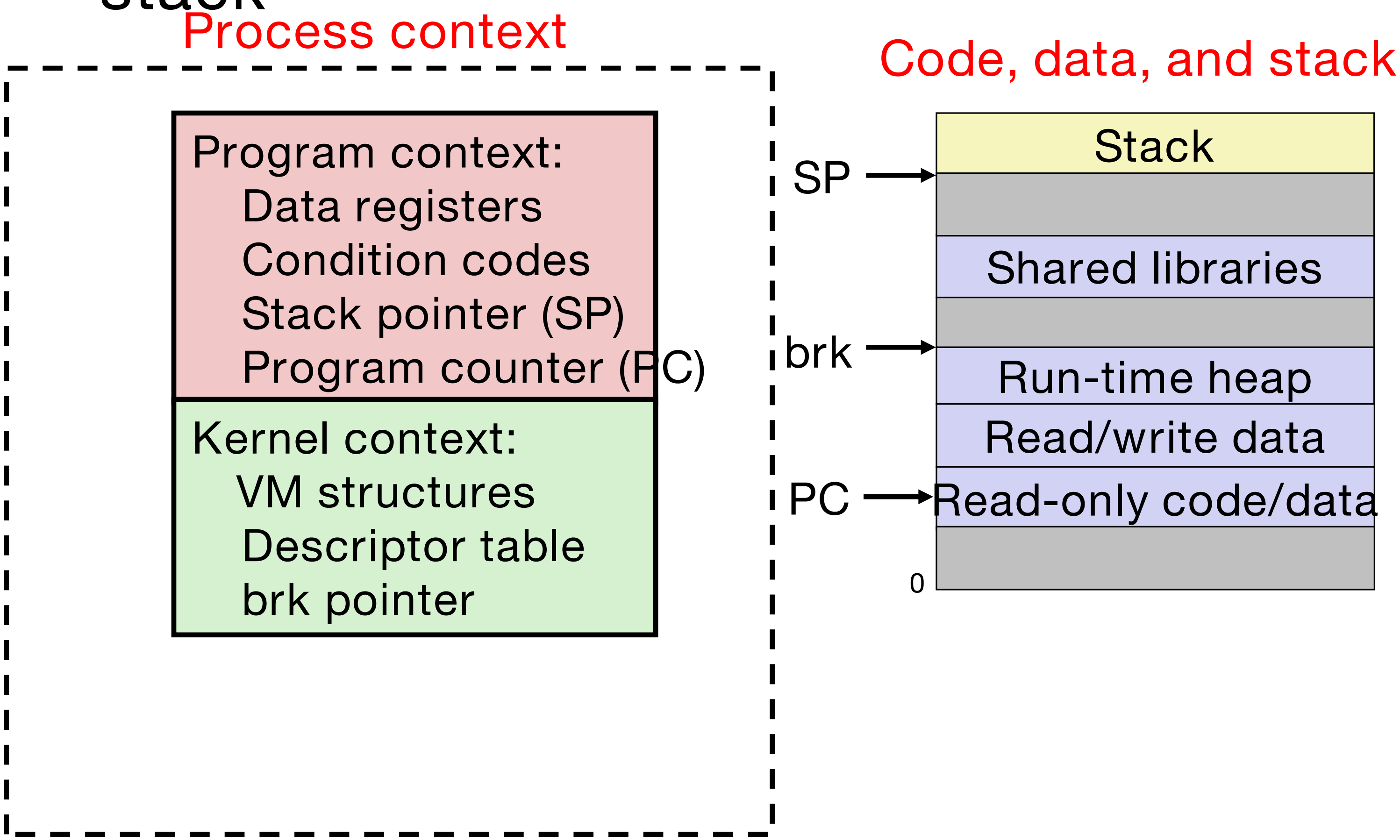
- – Significantly more complex to code than process- or thread-based designs.
- – Hard to provide fine-grained concurrency
  - E.g., how to deal with partial HTTP request headers
- – Cannot take advantage of multi-core
  - Single thread of control

Approach #3: Thread-based Servers

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

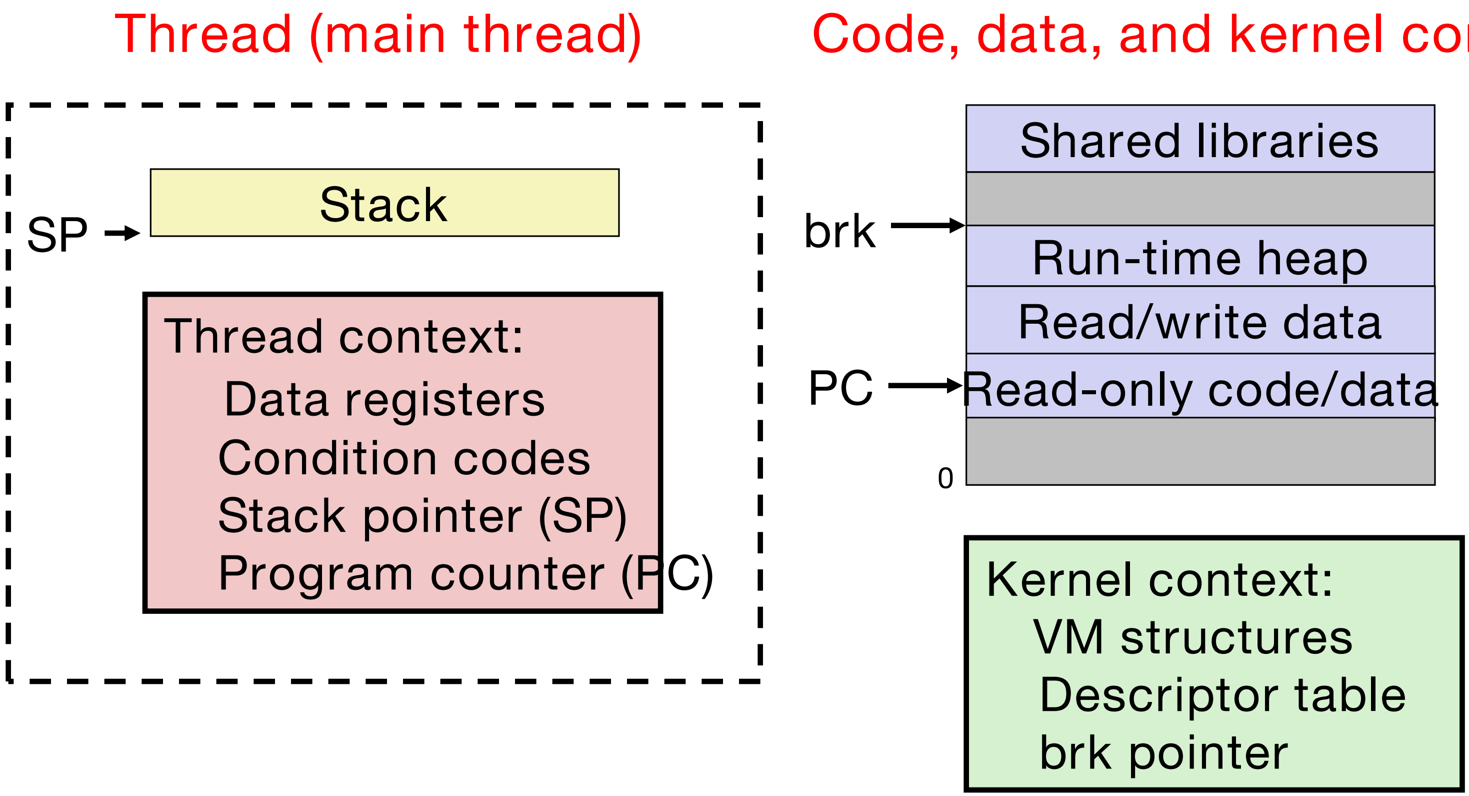
Traditional View of a Process

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



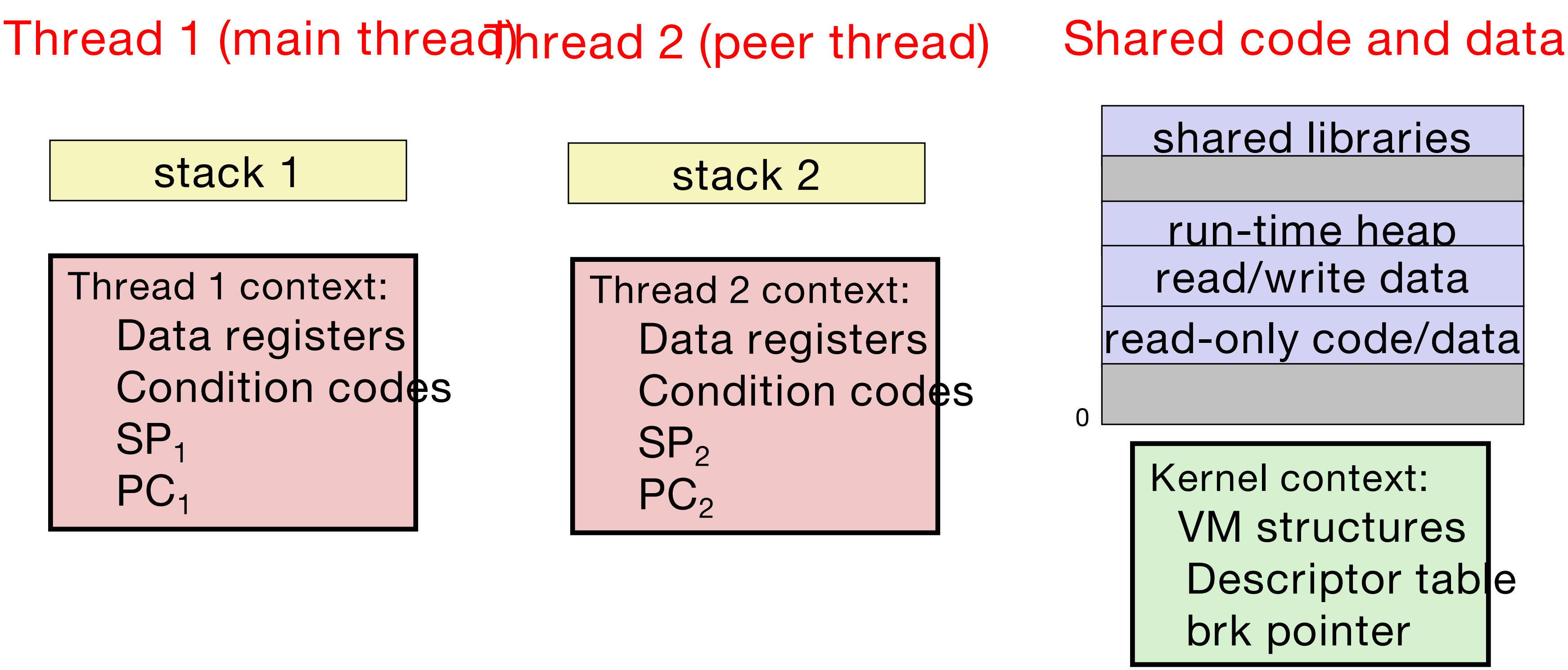
Alternate View of a Process

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



A Process With Multiple Threads

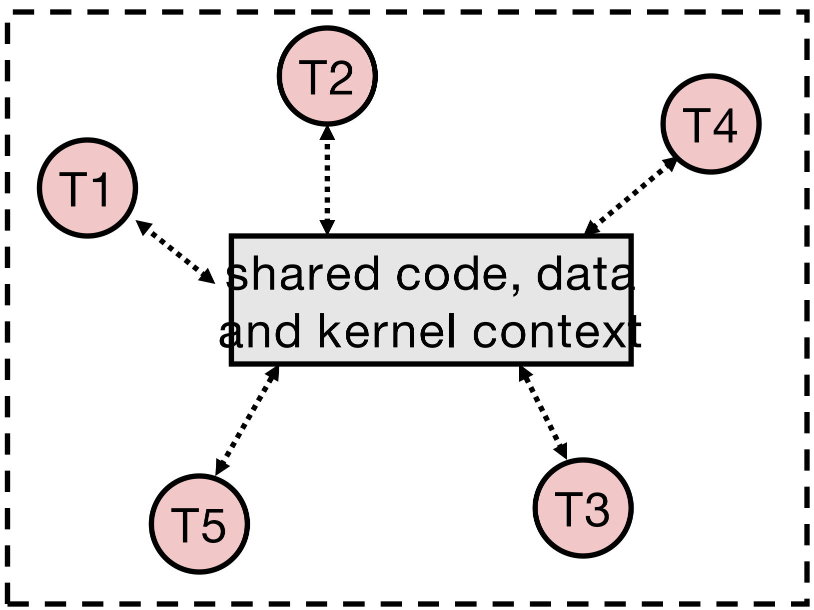
- Multiple threads can be associated with a process
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own stack for local variables
    - but not protected from other threads
  - Each thread has its own thread id (TID)



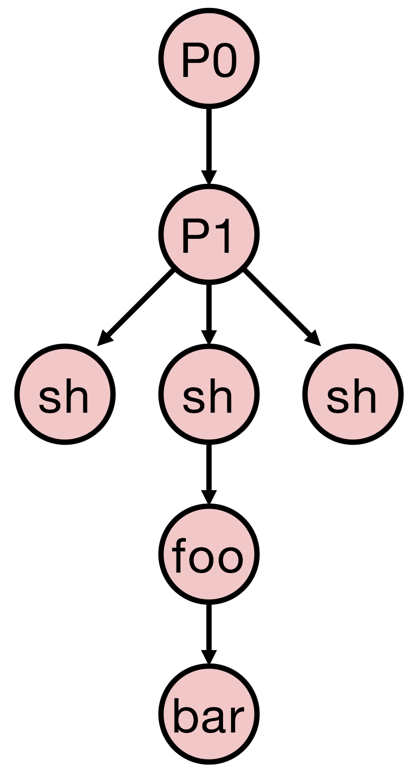
Logical View of Threads

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

Threads associated with process foo



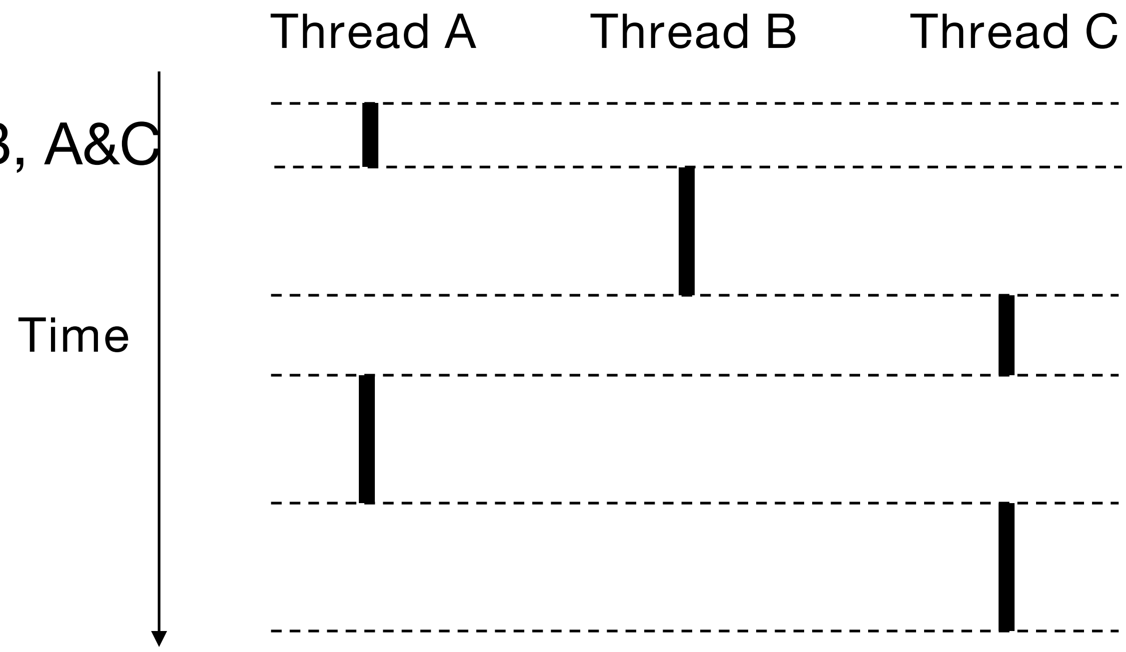
Process hierarchy



Concurrent Threads

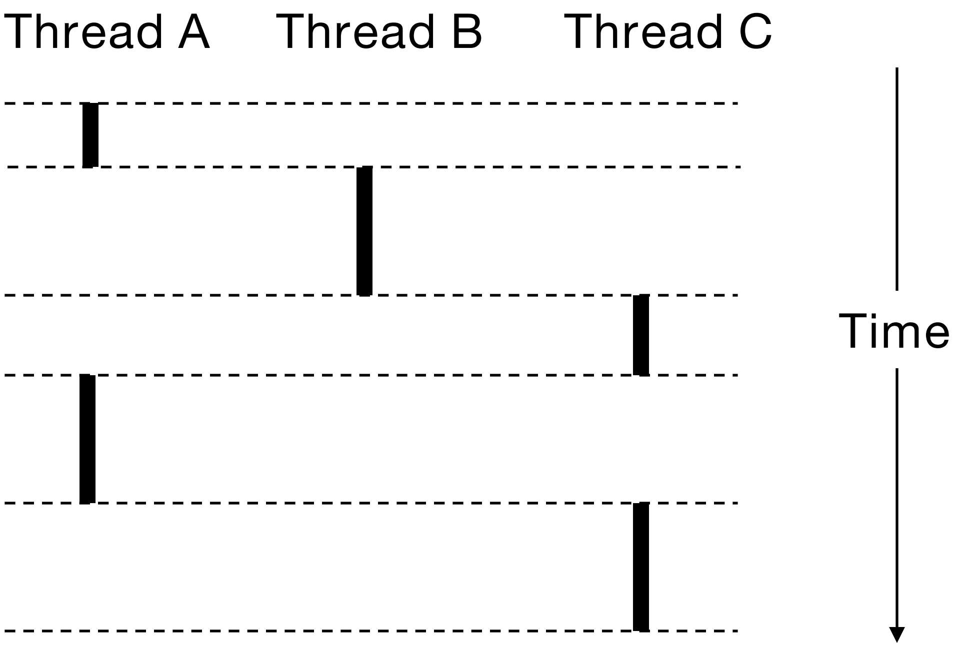
- Two threads are concurrent if their flows overlap in time
- Otherwise, they are sequential

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

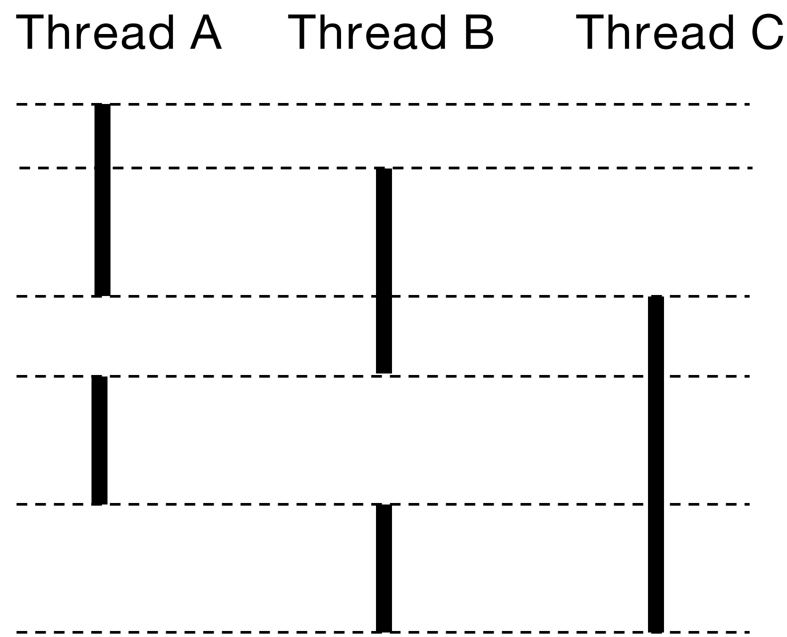


Concurrent Thread Execution

- Single Core Processor
  - Simulate parallelism by time slicing



- Multi-Core Processor
  - Can have true parallelism

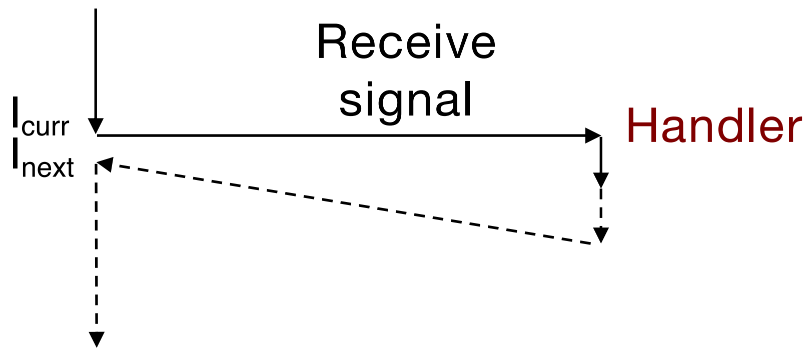


Run 3 threads on 2 cores

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
  - 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;
}
```

hello.c

Thread ID

Thread attributes (usually NULL)

Thread routine

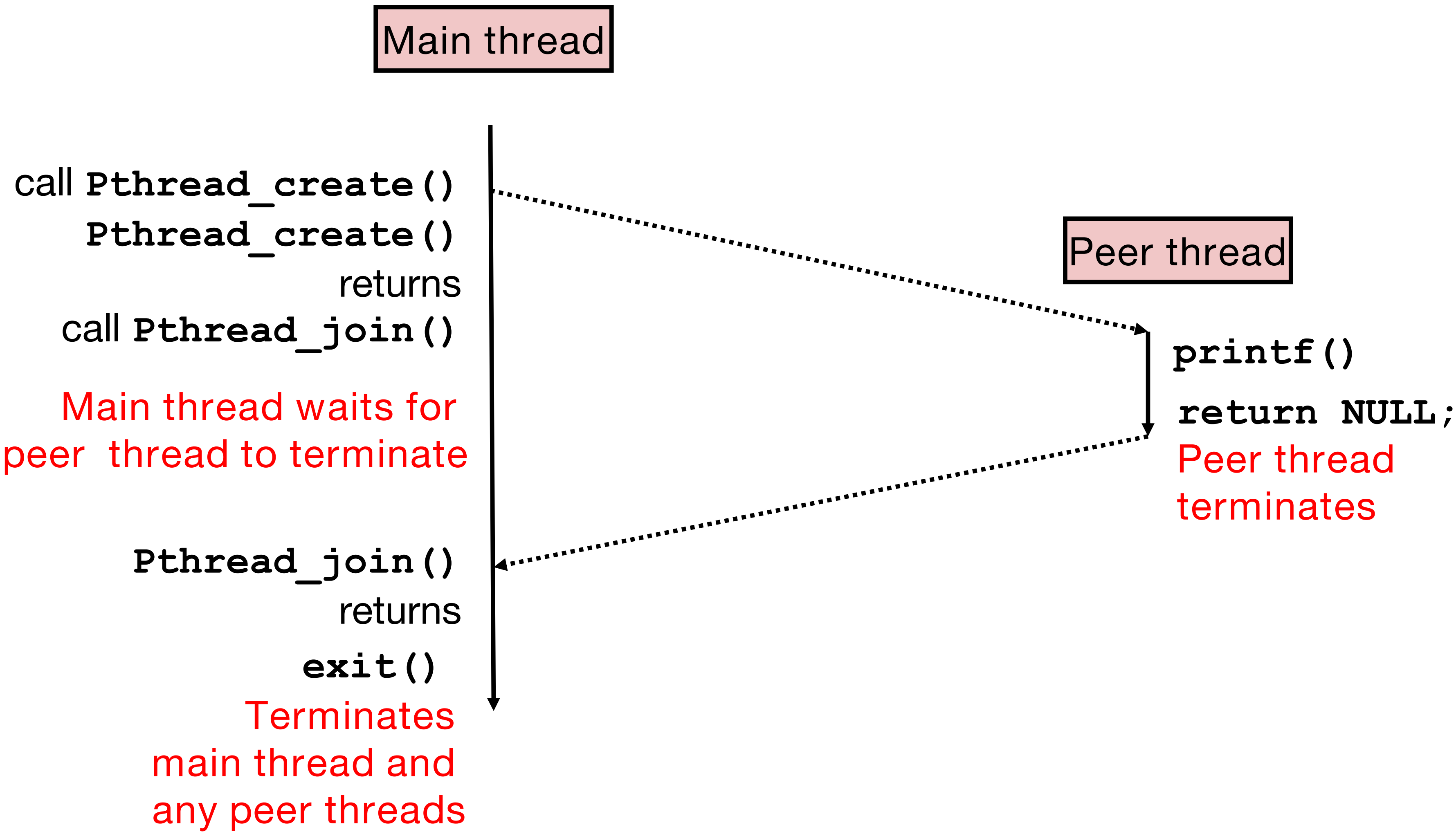
Thread arguments (void *p)

Return value (void **p)

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

hello.c

Execution of Threaded "hello, world"



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()`**]

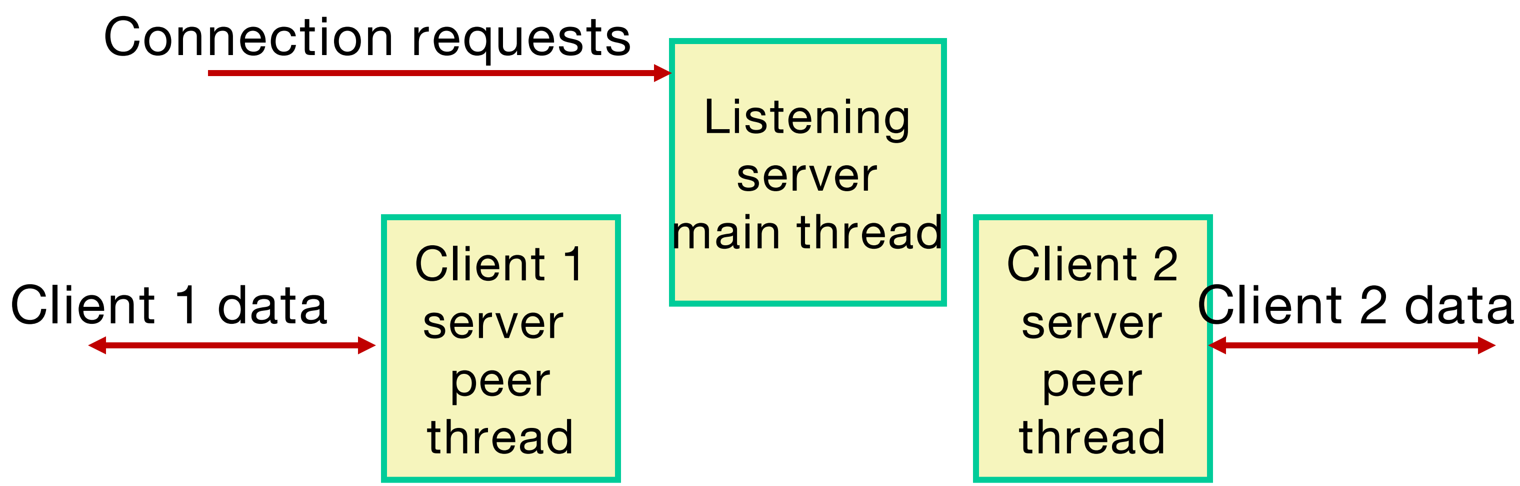
Thread-Based Concurrent Server (cont)

```
/* 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



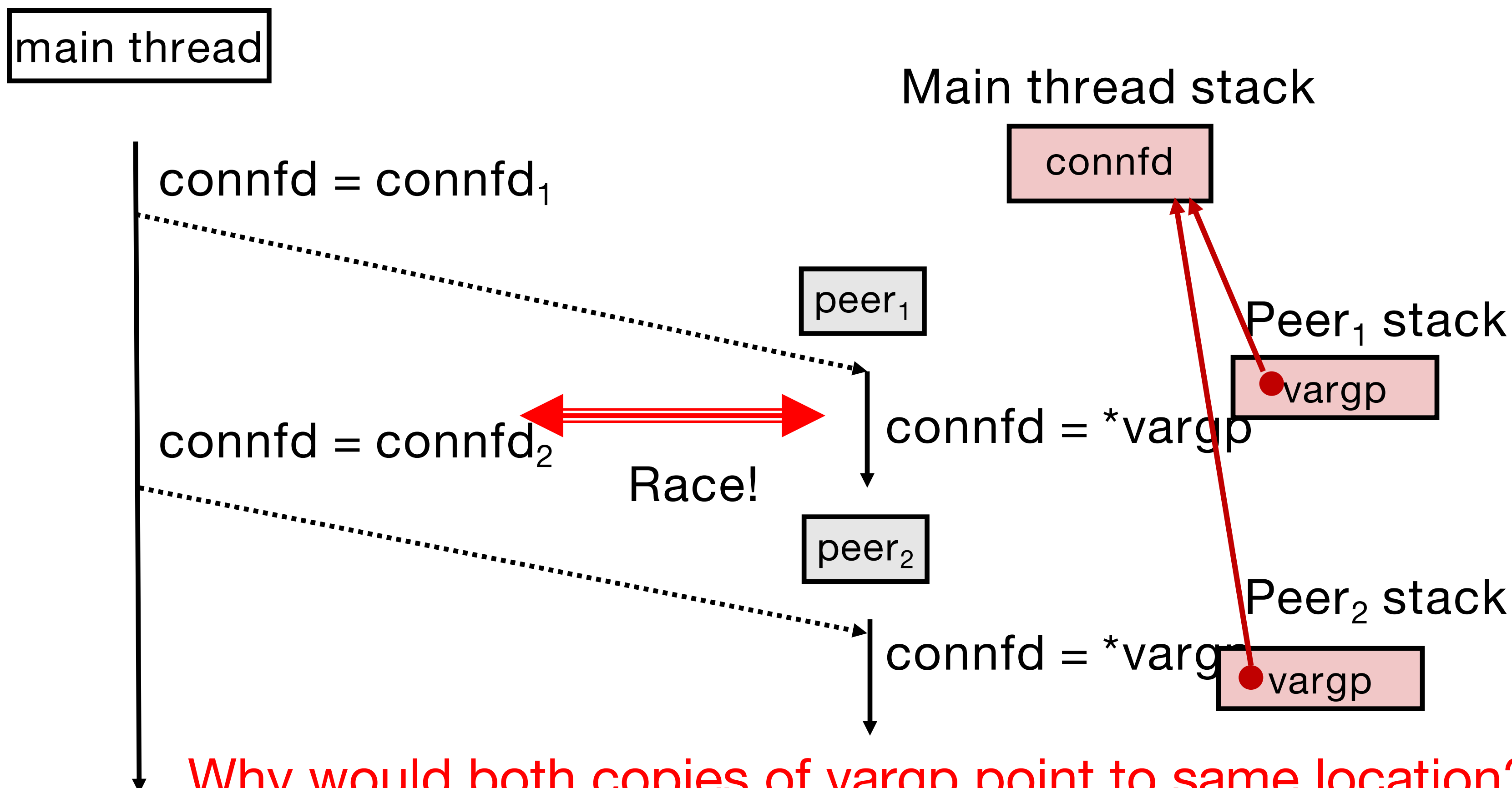
- Each client handled by individual peer thread
- Threads share all process state except TID
- Each thread has a separate stack for local variables

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?

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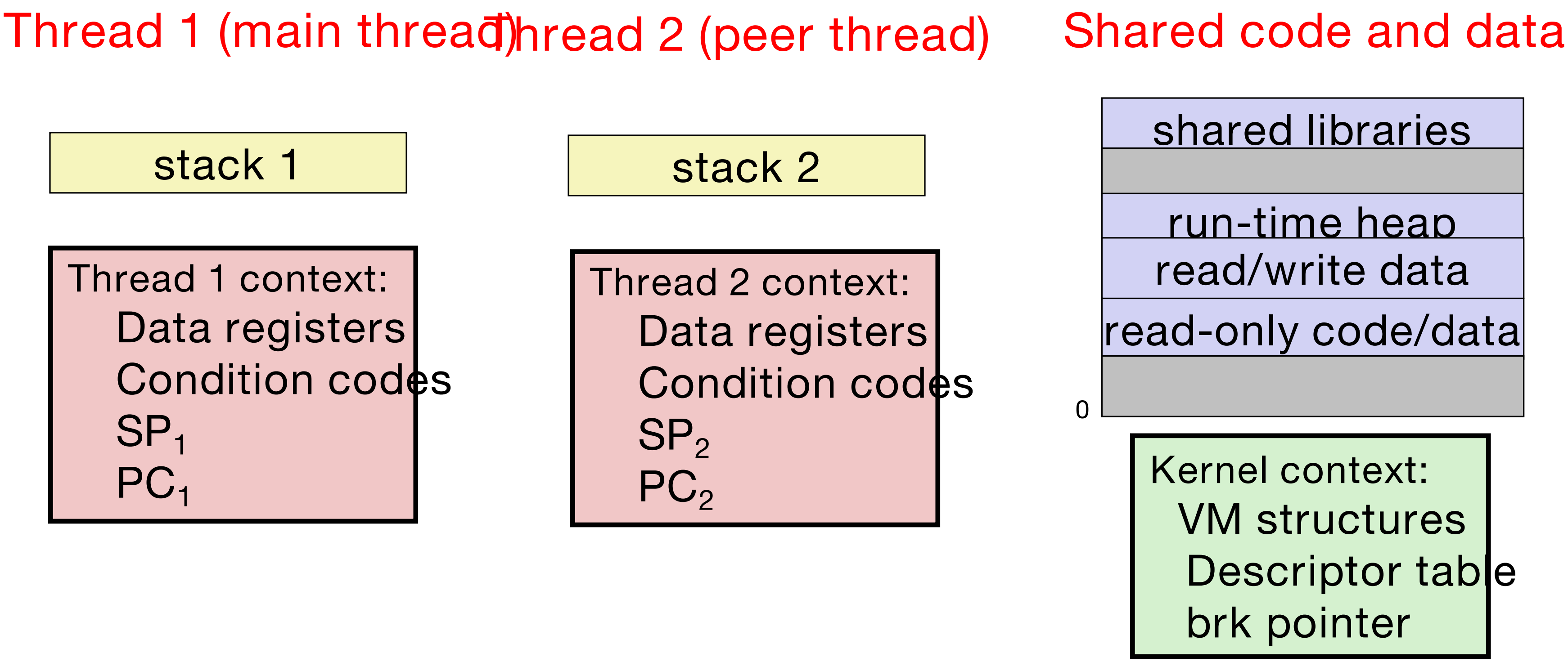


But ALL memory is shared

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

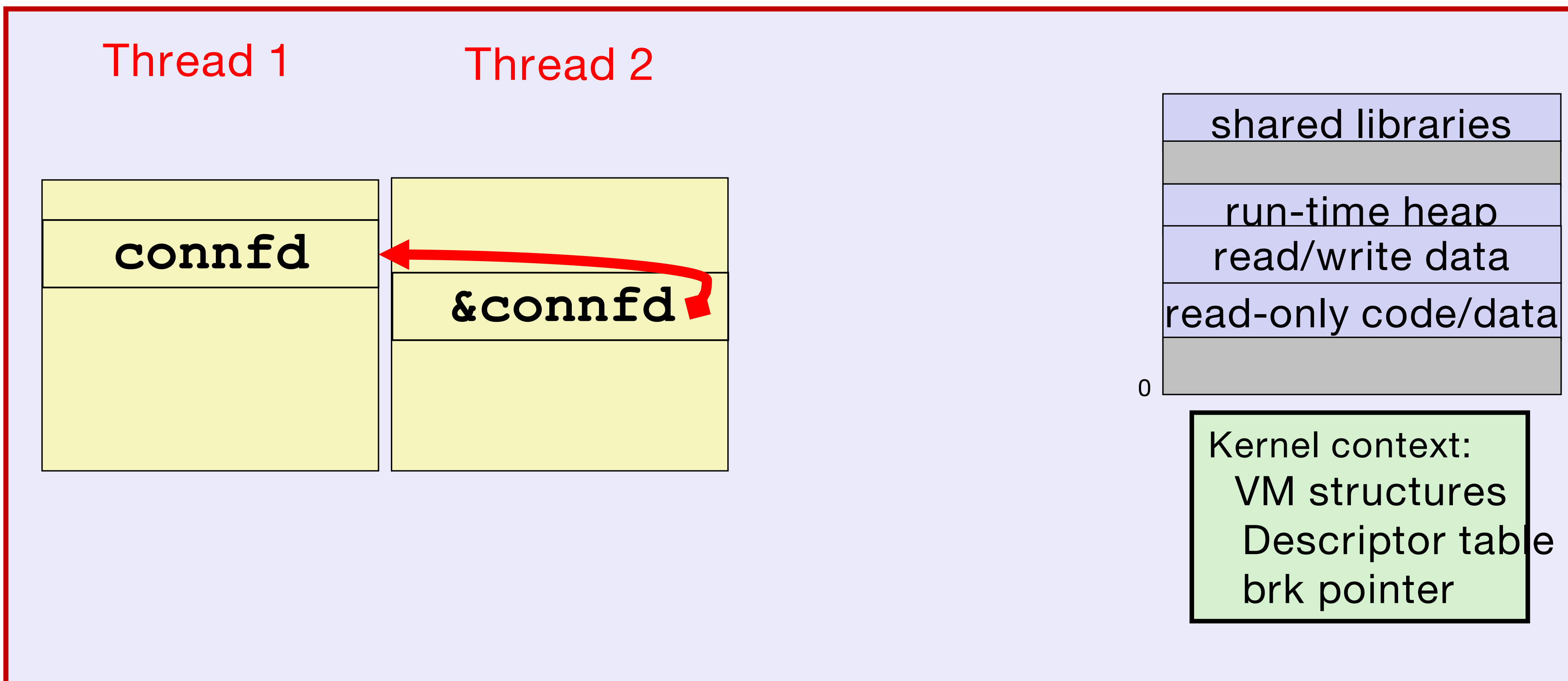
0

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_1
- PC_1

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

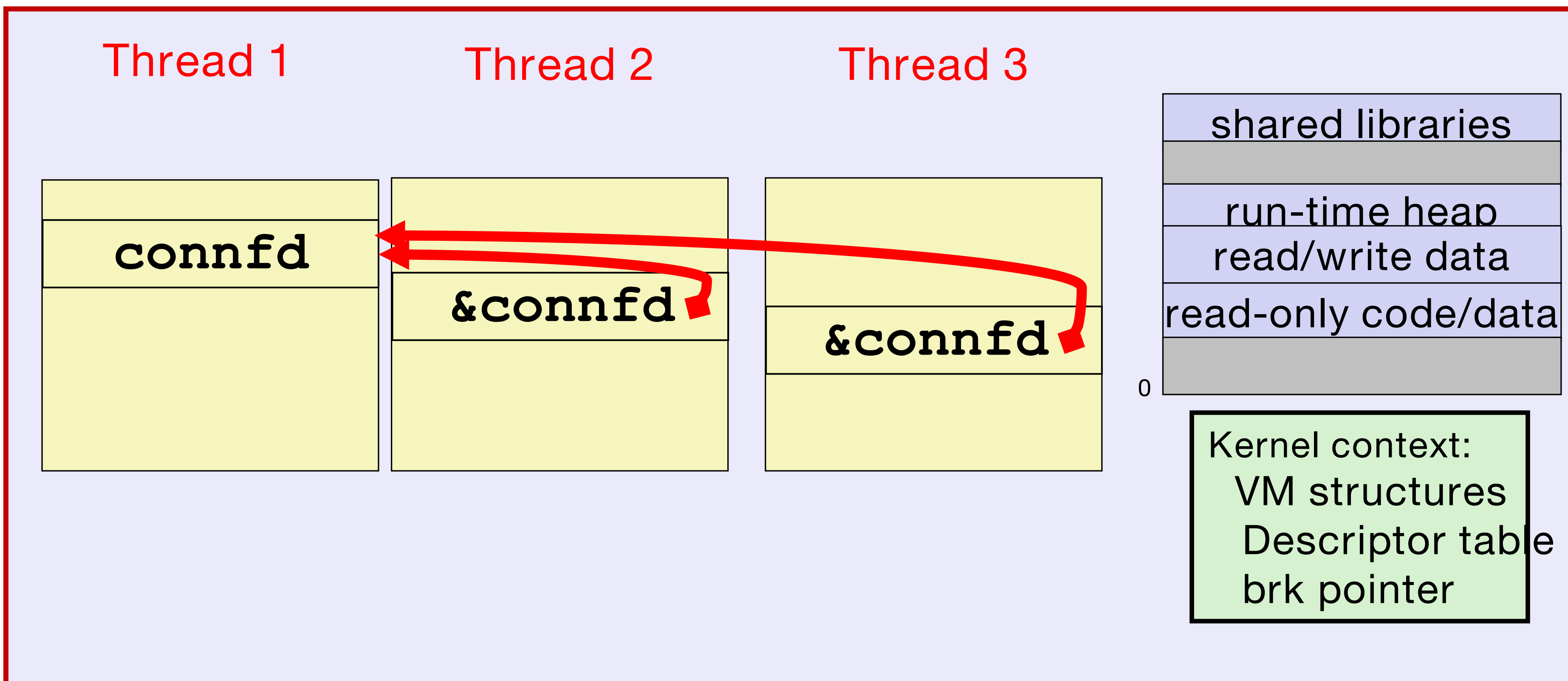


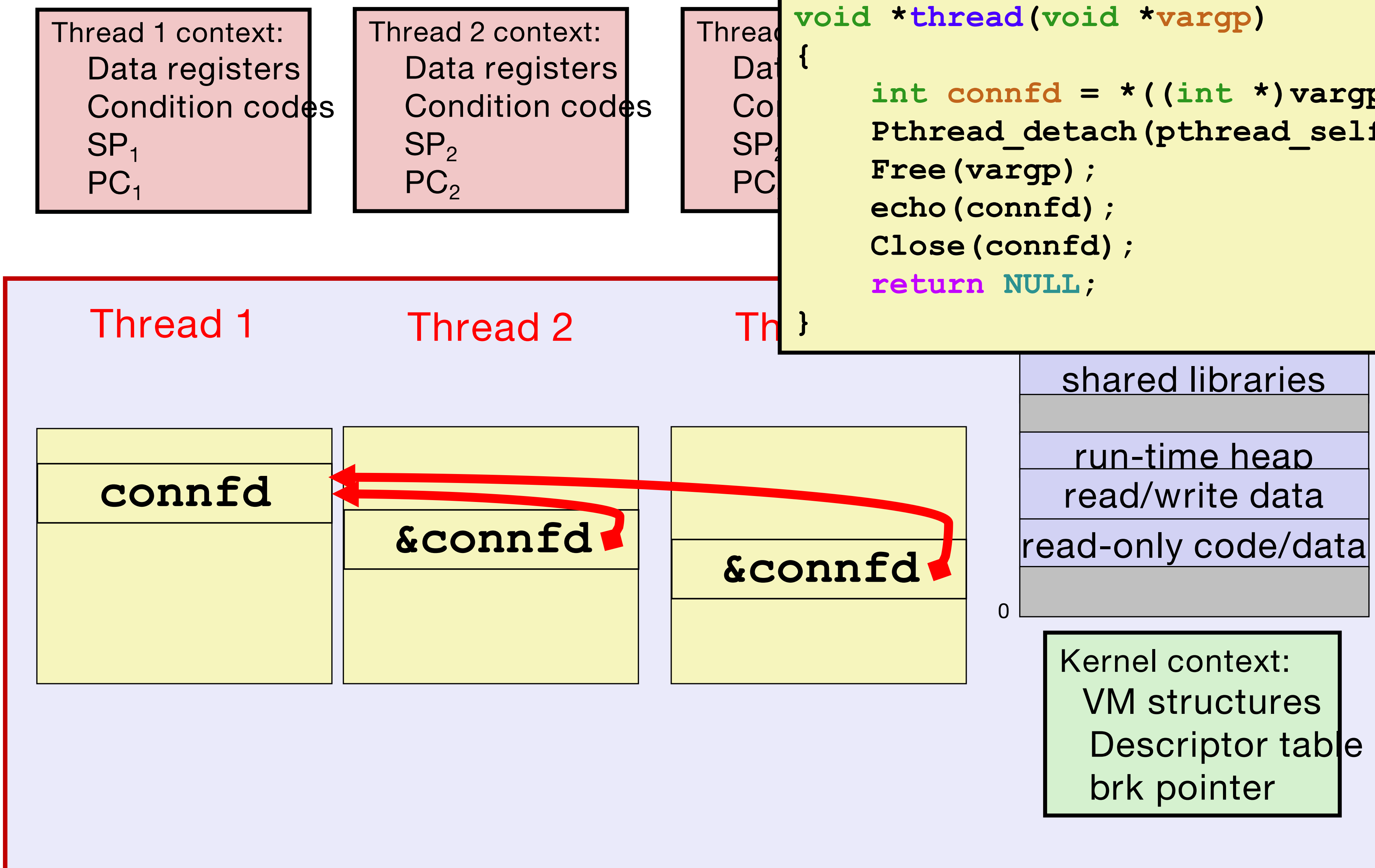
```c
while (1) {
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
    Pthread_create(&tid, NULL, thread, &connfd);
}
```

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);
}
```

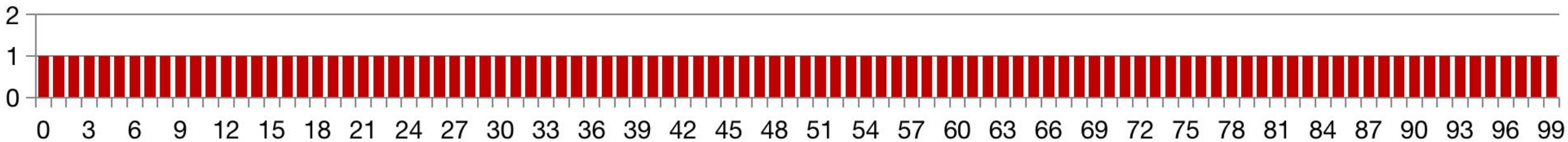
Thread

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

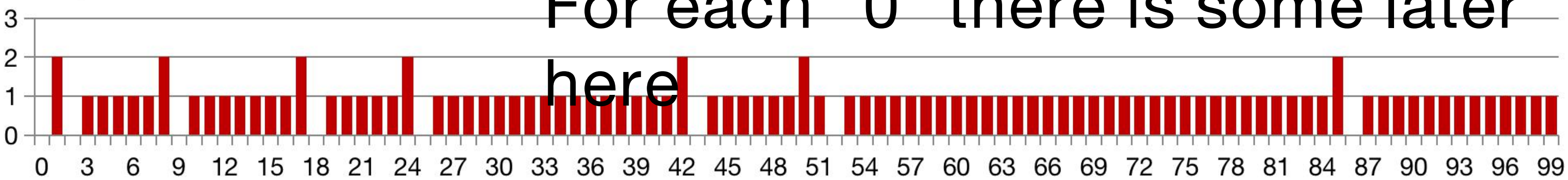
- Race Test
  - If no race, then each thread would get different value of **`i`**
  - Set of saved values would consist of one copy each of 0 through 99

Experimental Results

No Race

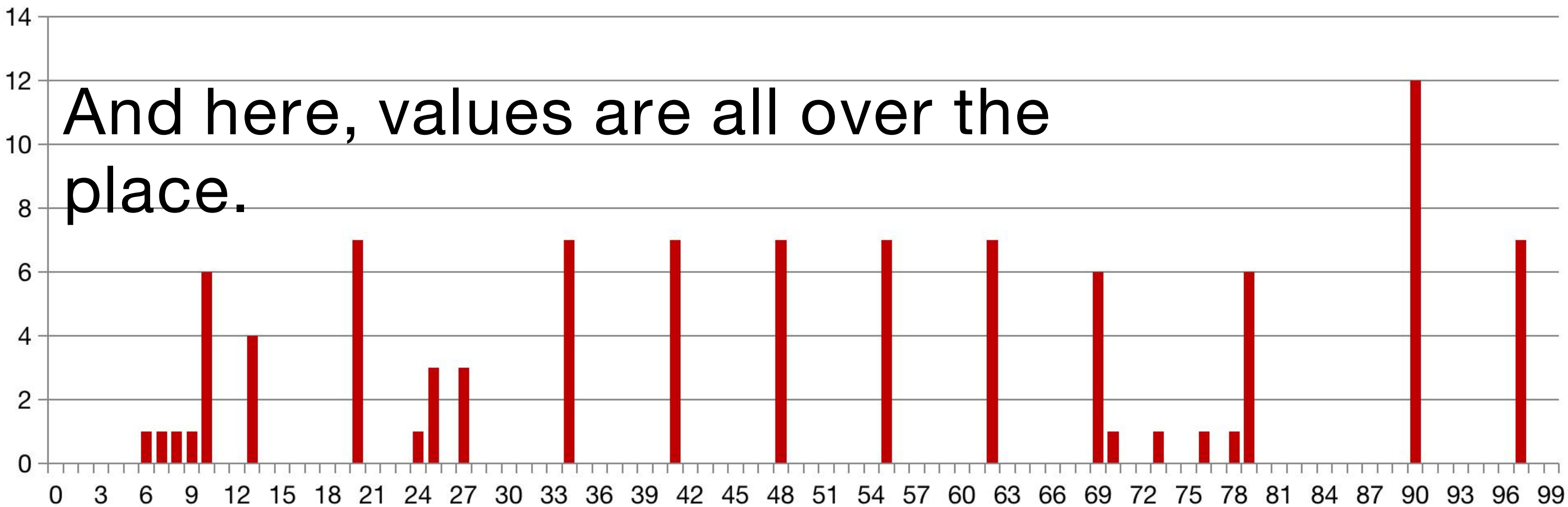


Single core laptop



For each “0” there is some later “2” here

Multicore server



And here, values are all over the place.

- Some bins get no update, some get 2 (or more!)

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