Concurrent Programming

15-213 / 18-213: Introduction to Computer Systems
23rd Lecture, April 15, 2014

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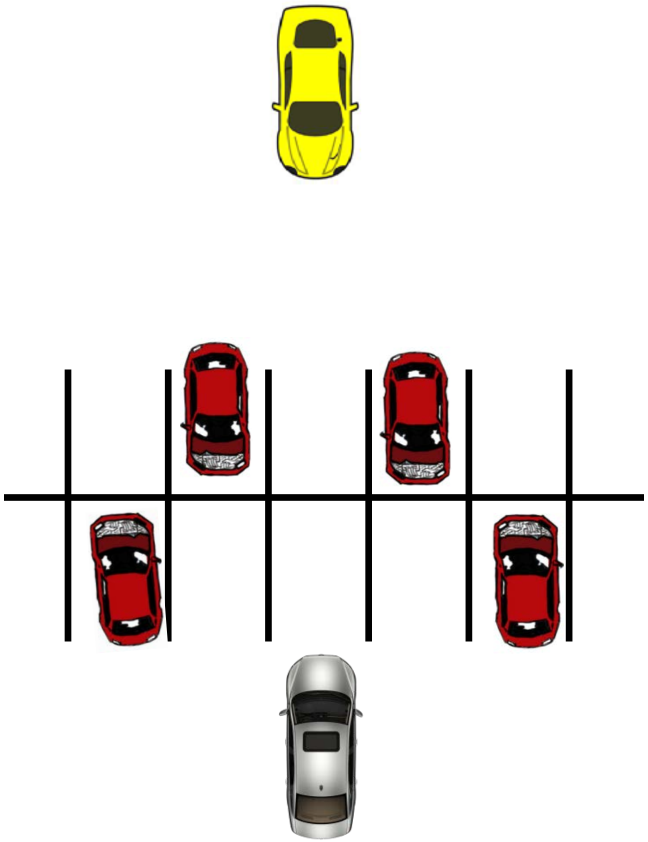
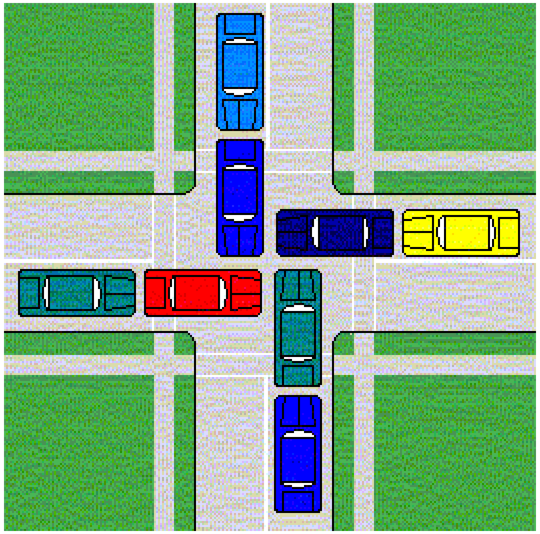
Concurrent Programming is Hard!

- 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

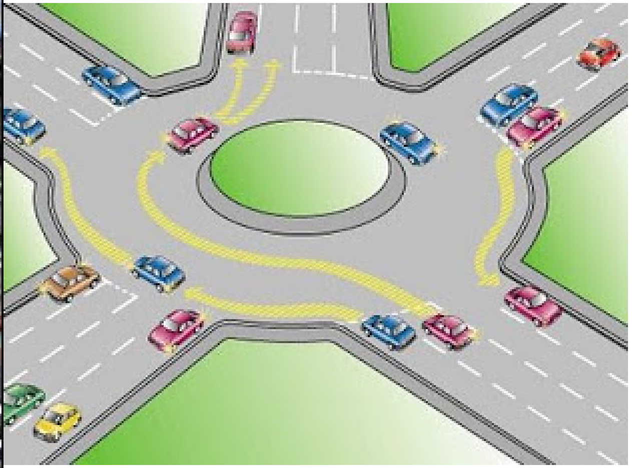
Data Race



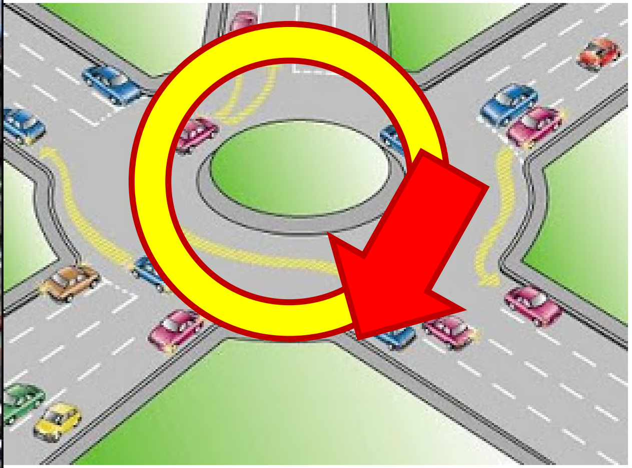
Deadlock



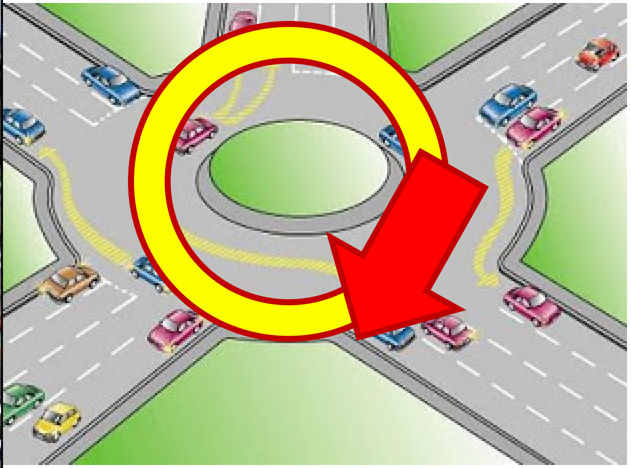
Livelock



Livelock



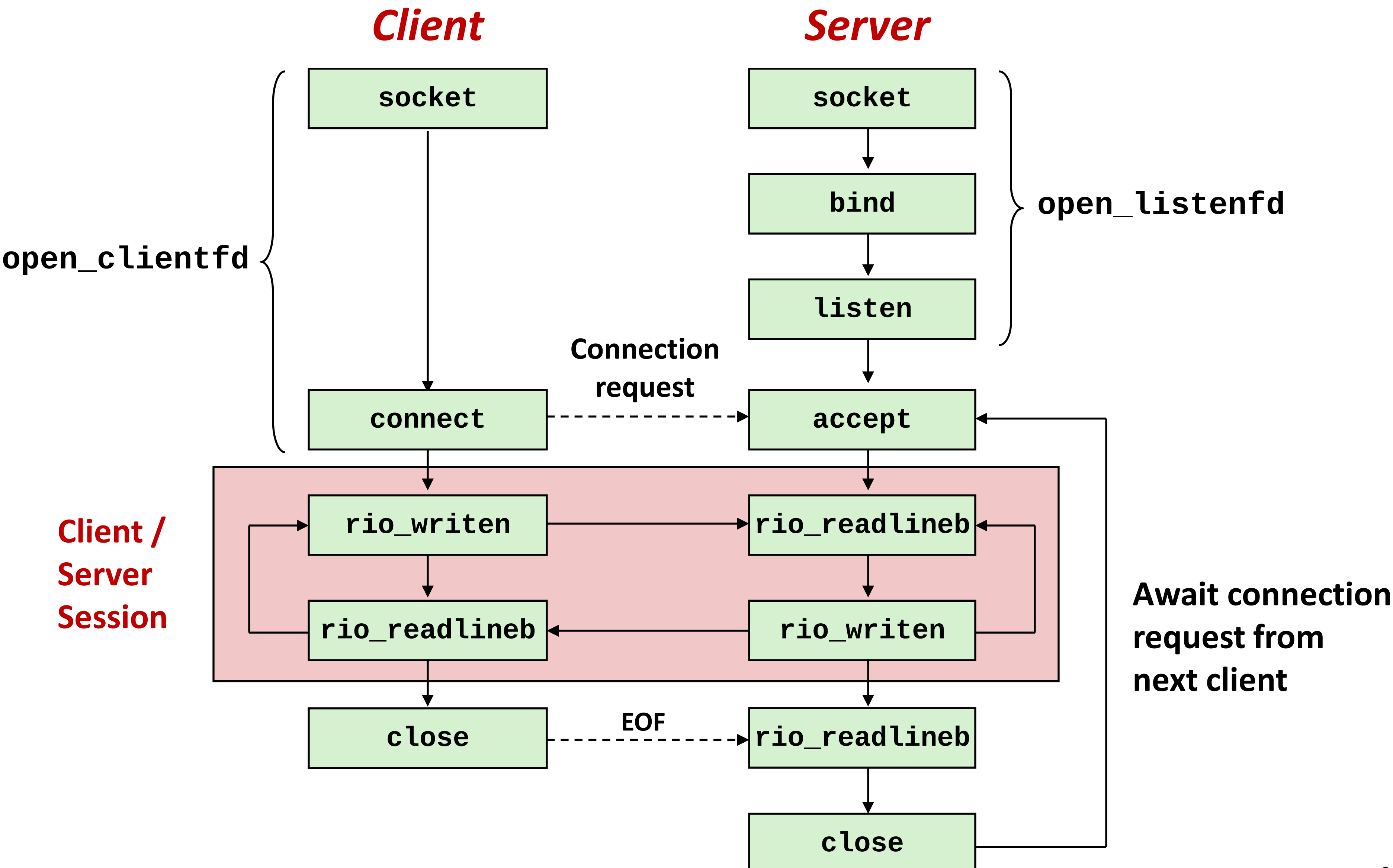
Livelock



Concurrent Programming is Hard!

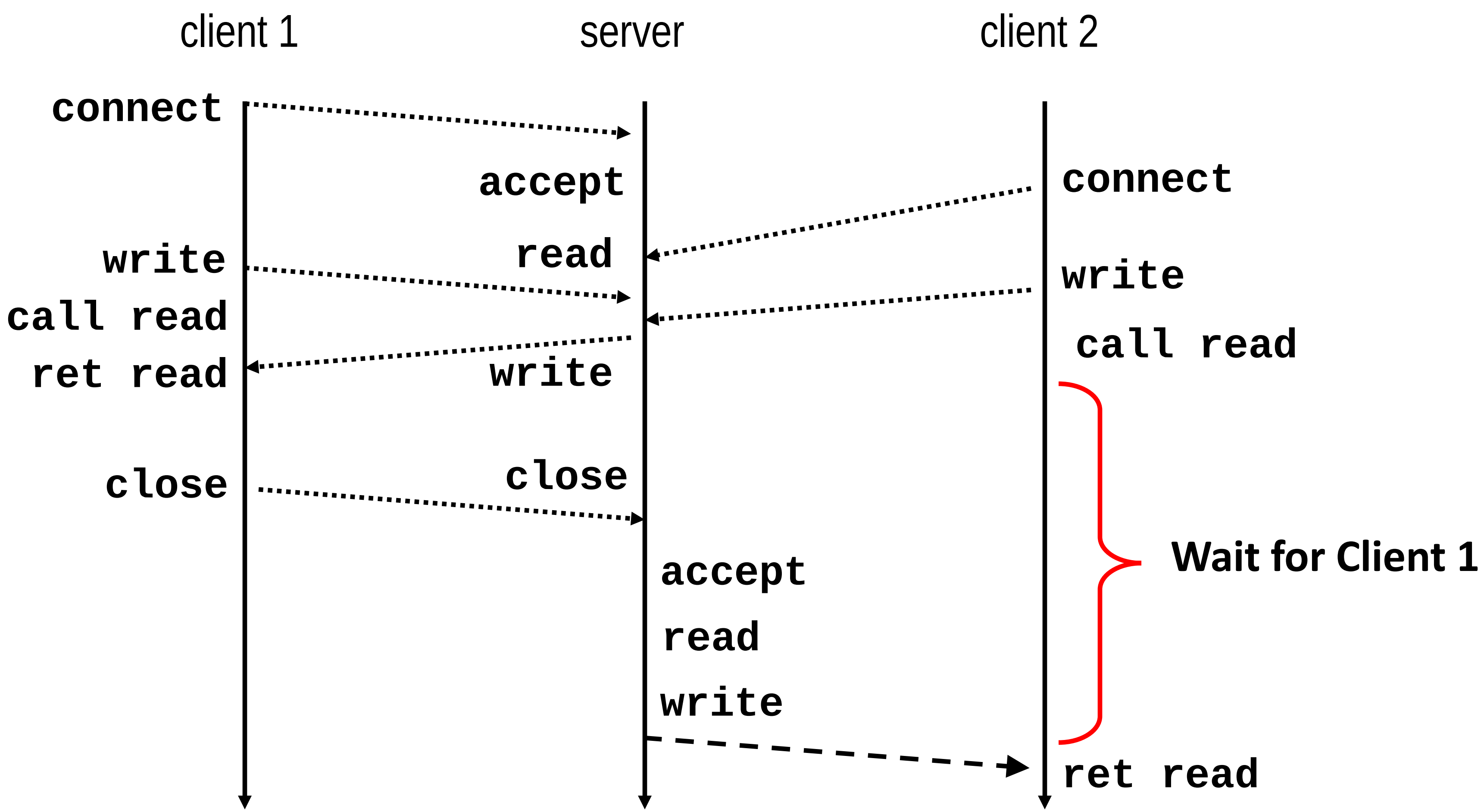
- **Classical problem classes of concurrent programs:**
  - ***Races:*** outcome depends on arbitrary scheduling decisions elsewhere in the system
    - Example: who gets the last seat on the airplane?
  - ***Deadlock:*** improper resource allocation prevents forward progress
    - Example: traffic gridlock
  - ***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 15-213**
  - but, not all ☺

Reminder: Iterative Echo Server



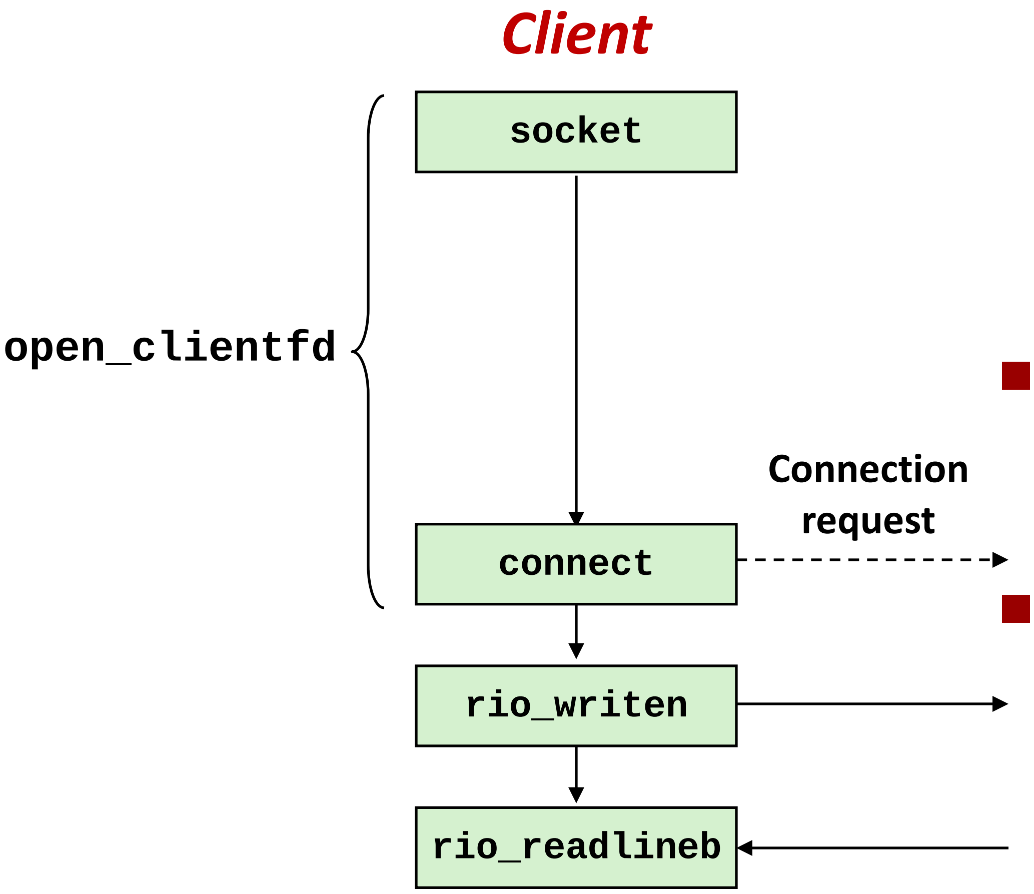
Iterative Servers

- Iterative servers process one request at a time



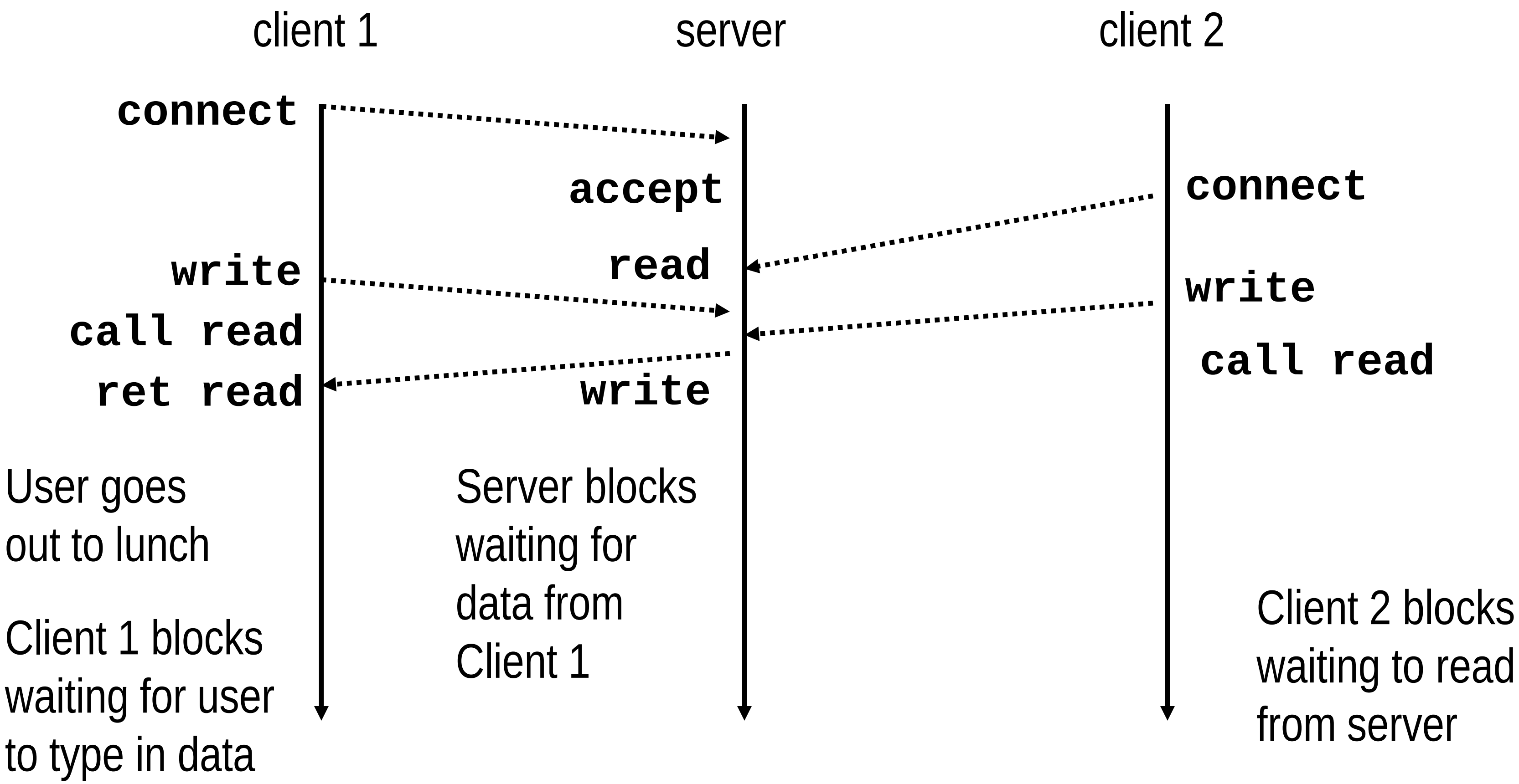
Where Does Second Client Block?

- **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

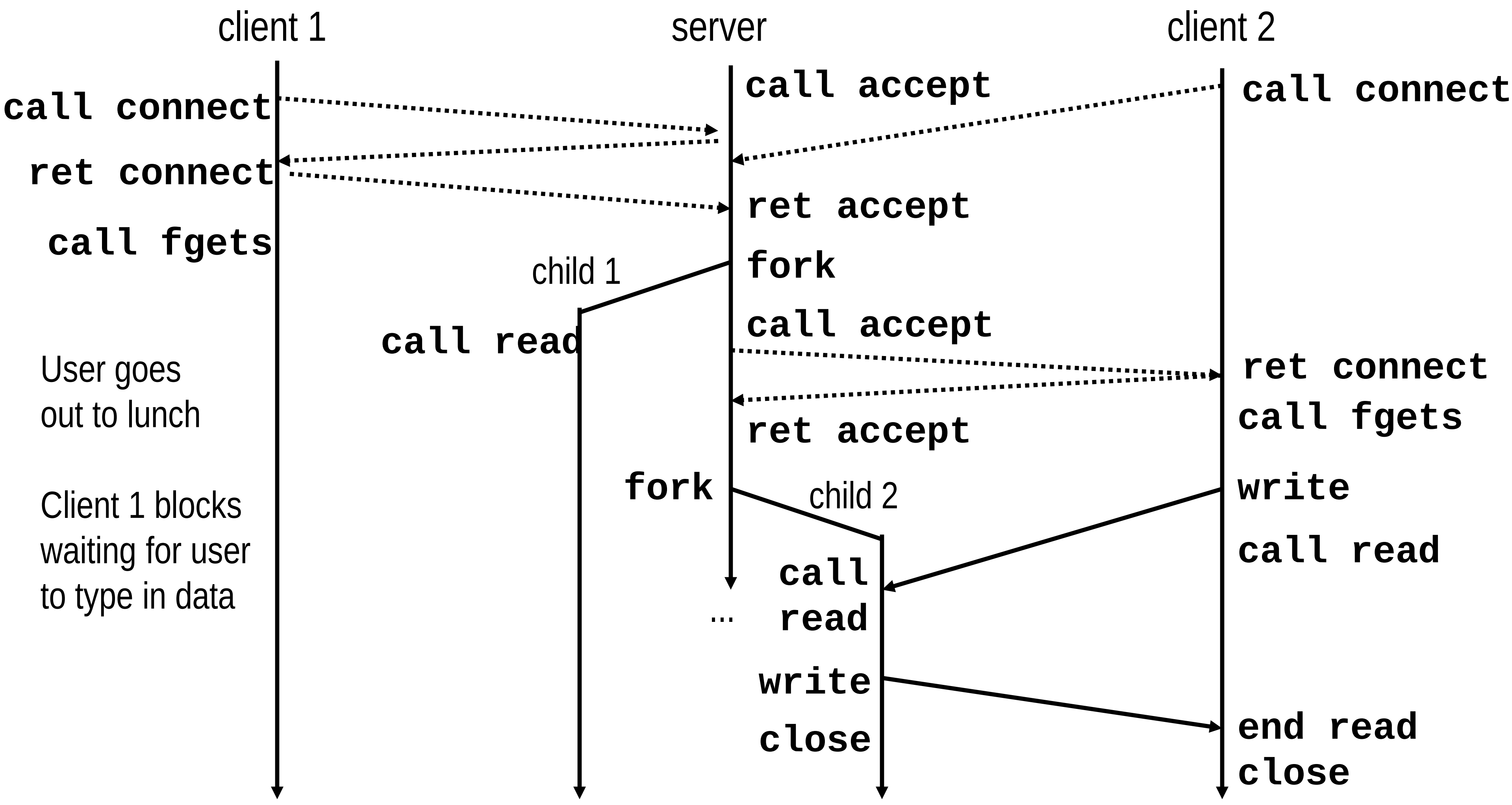
Server concurrency (3 approaches)

Allow server to handle multiple clients simultaneously

- **1. Processes**
  - Kernel automatically interleaves multiple logical flows
  - Each flow has its own private address space
- **2. Threads**
  - Kernel automatically interleaves multiple logical flows
  - Each flow shares the same address space
- **3. I/O multiplexing with `select()`**
  - Programmer manually interleaves multiple logical flows
  - All flows share the same address space
  - Relies on lower-level system abstractions

Concurrent Servers: Multiple Processes

- Spawn separate process for each client



Review: Iterative Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen = sizeof(clientaddr);

    listenfd = Open_listenfd(port);
    while (1) {
       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;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen=sizeof(clientaddr);


    listenfd = Open_listenfd(port);
    while (1) {
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);


            echo(connfd);    /* Child services client */
            Close(connfd);   /* Child closes connection with client */




    }
}
```

Making A Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen=sizeof(clientaddr);


    listenfd = Open_listenfd(port);
    while (1) {
        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 */
        }

    }
}
```

Making A Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen=sizeof(clientaddr);

    Signal(SIGCHLD, sigchld_handler);
    listenfd = Open_listenfd(port);
    while (1) {
        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 */
        }

    }
}
```

Making A Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen=sizeof(clientaddr);

    Signal(SIGCHLD, sigchld_handler);
    listenfd = Open_listenfd(port);
    while (1) {
       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 */
       }

    }
}
```

Making A Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen=sizeof(clientaddr);

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

Process-Based Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen=sizeof(clientaddr);

    Signal(SIGCHLD, sigchld_handler);
    listenfd = Open_listenfd(port);
    while (1) {
        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!) */
    }
}
```

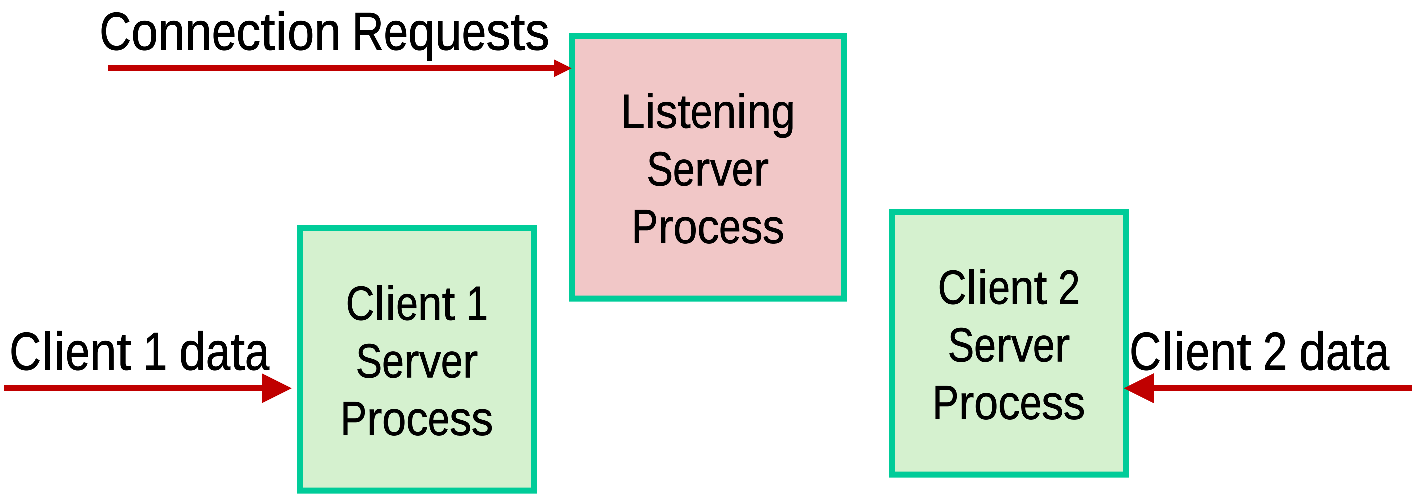
Fork separate process for each client
Does not allow any communication between different client handlers

Process-Based Concurrent Echo Server (cont)

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

- Reap all zombie children

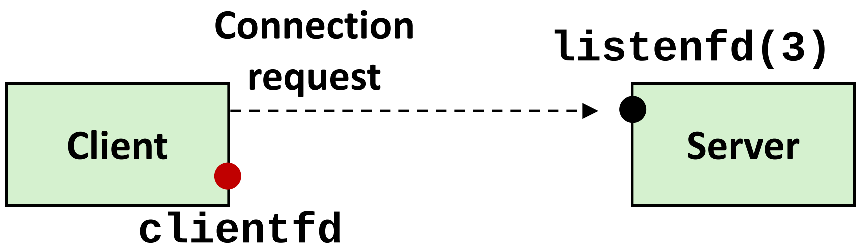
Process Execution Model



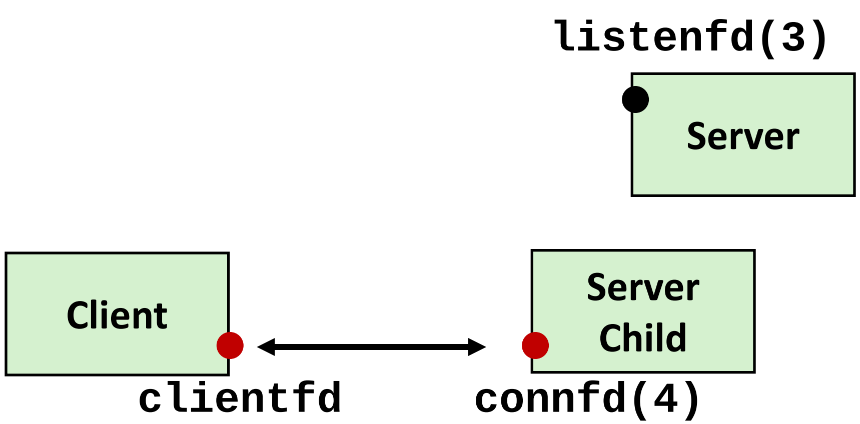
- Each client handled by independent process
- No shared state between them
- Both parent & child have copies of listenfd and connfd
  - Parent must close connfd
  - Child must close listenfd

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`

Implementation Must-dos With Process-Based Designs

- **Listening server process must reap zombie children**
  - to avoid fatal memory leak
- **Listening server process must `close` its copy of `connfd`**
  - Kernel keeps reference 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 Designs

- **+ 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**
  - Requires IPC (interprocess communication) mechanisms
    - FIFO’s (named pipes), System V shared memory and semaphores

Approach #2: Multiple Threads

- **Very similar to approach #1 (multiple processes)**
  - but, with threads instead of processes

Traditional View of a Process

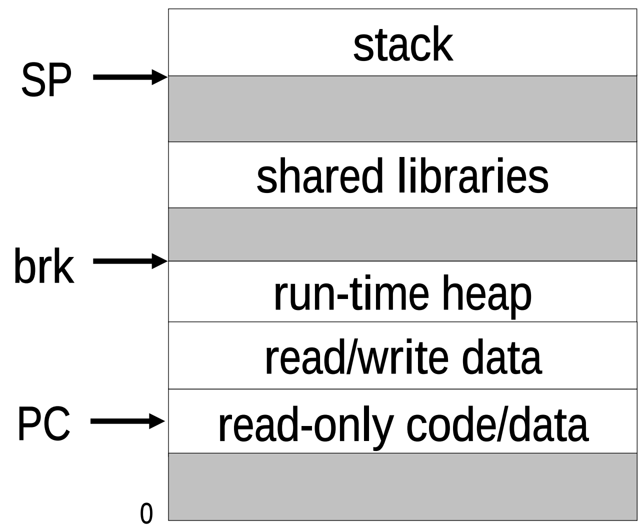
- **Process = process context + code, data, and stack**

Process context

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

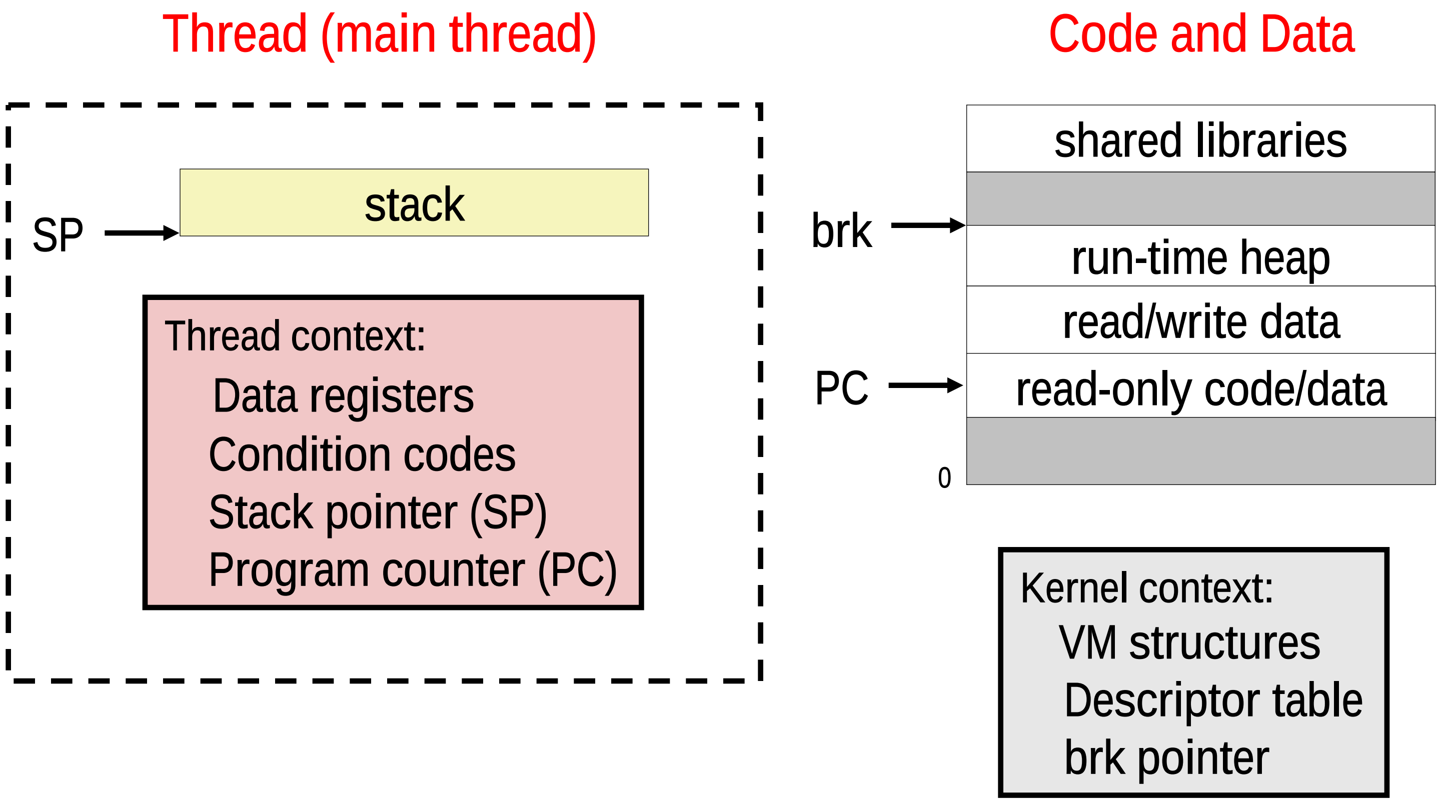
Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack



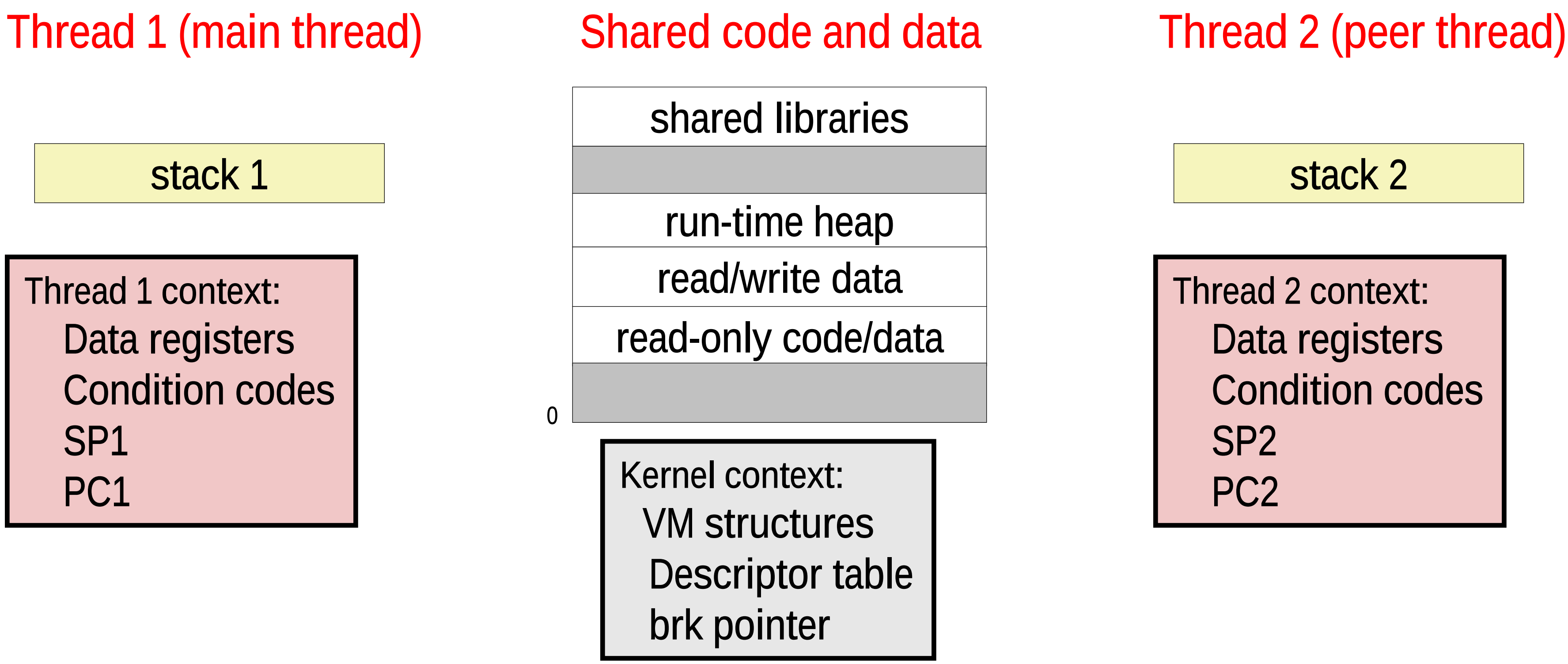
Alternate View of a Process

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



A Process With Multiple Threads

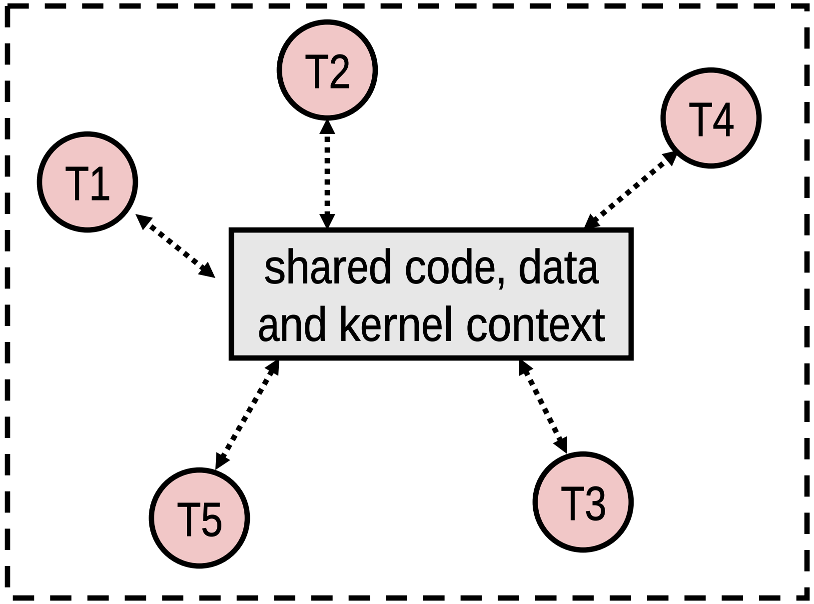
- **Multiple threads can be associated with a process**
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
    - Share common virtual address space (inc. stacks)
  - Each thread has its own thread id (TID)



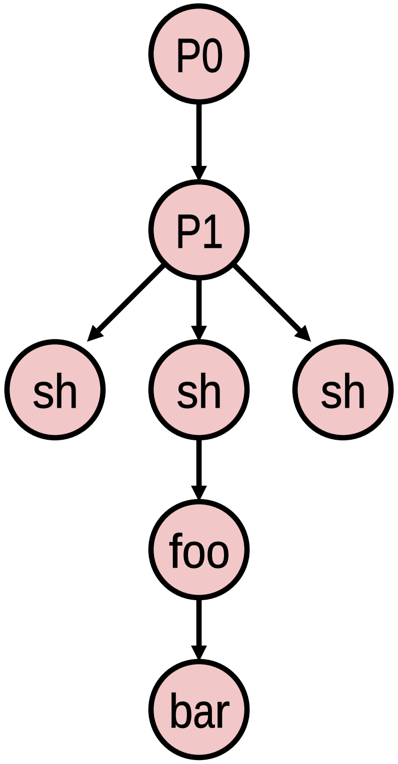
Logical View of Threads

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

Threads associated with process foo

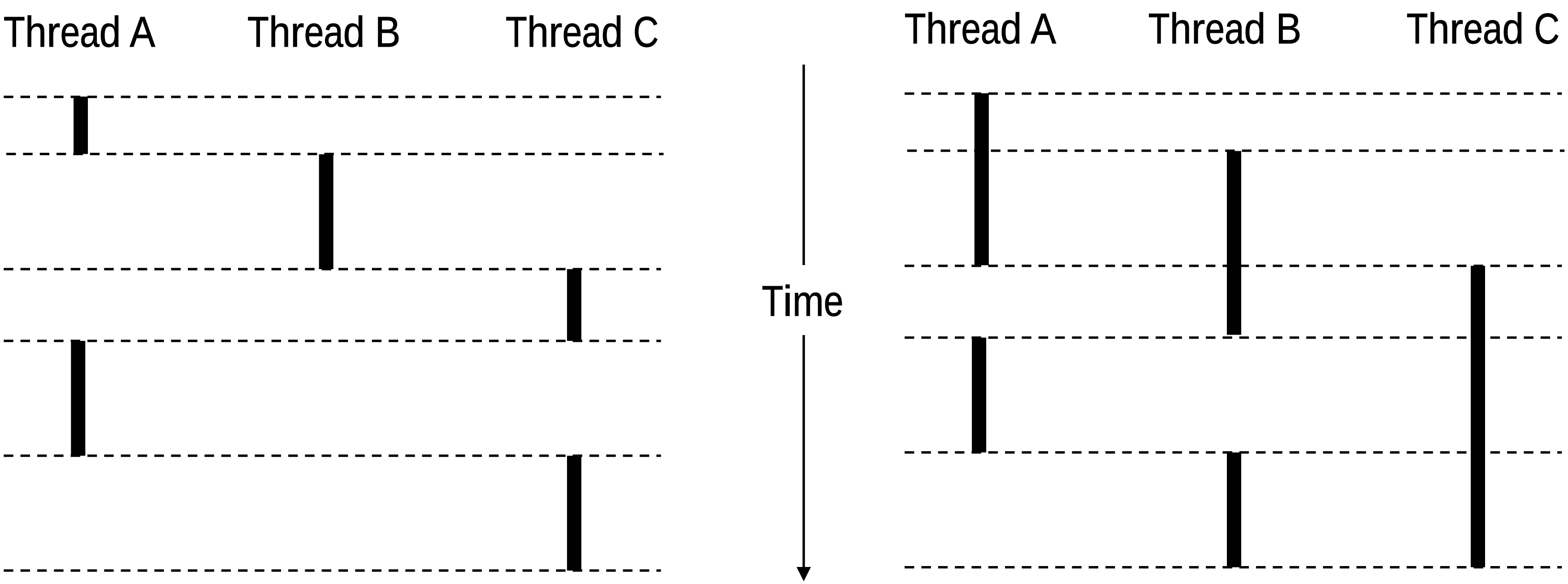


Process hierarchy



Thread Execution

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

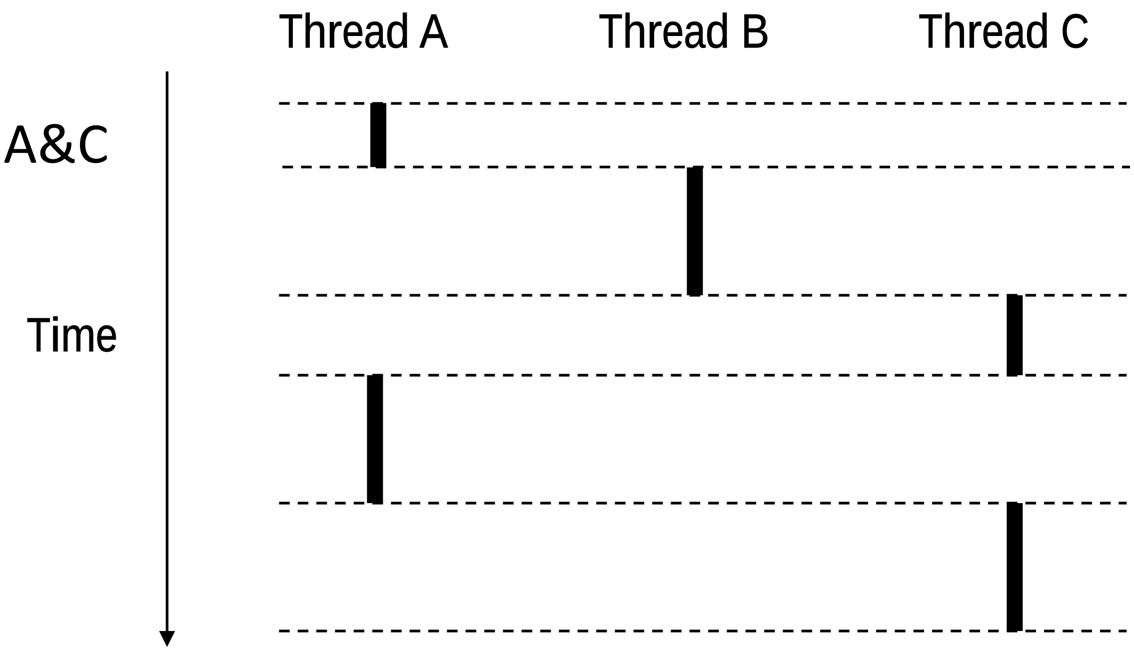


Run 3 threads on 2 cores

Logical Concurrency

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

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



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 code and some data
    - Processes (typically) do not
  - Threads are somewhat less expensive than processes
    - Process control (creating and reaping) twice as expensive as thread control
    - Linux numbers:
      - ~20K cycles to create and reap a process
      - ~10K cycles (or less) to create and reap a thread

Posix Threads (Pthreads) Interface

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

The Pthreads "hello, world" Program

```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

void *thread(void *vargp);

int main() {
  pthread_t tid;

  Pthread_create(&tid, NULL, thread, NULL);
  Pthread_join(tid, NULL);
  exit(0);
}
```

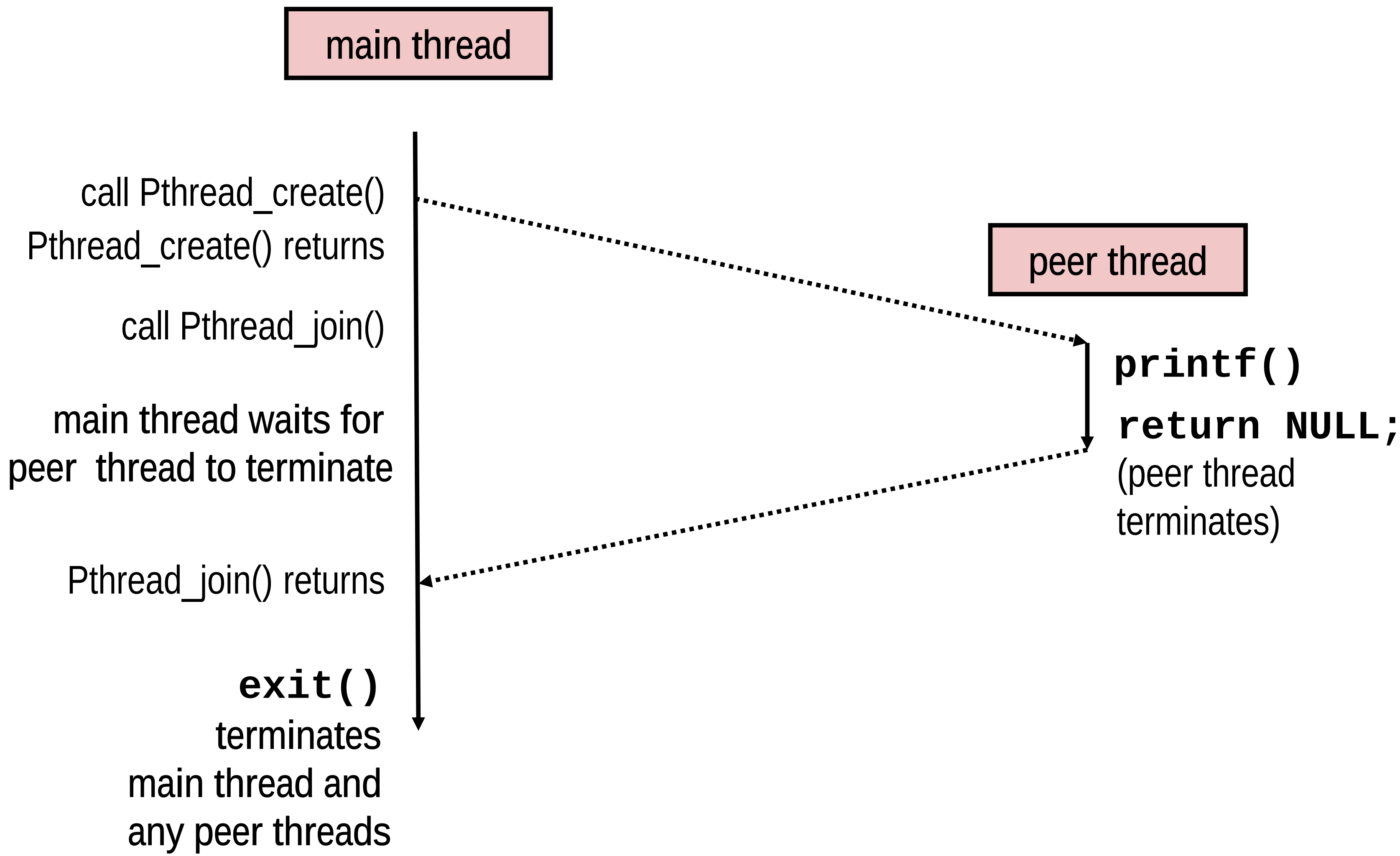
```
/* thread routine */
void *thread(void *vargp) {
  printf("Hello, world!\n");
  return NULL;
}
```

Thread attributes (usually NULL)

*Thread arguments (void *p)*

*return value (void **p)*

Execution of Threaded"hello, world"



Thread-Based Concurrent Echo Server

```
int main(int argc, char **argv) {
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen=sizeof(clientaddr);
    pthread_t tid;

    int listenfd = Open_listenfd(port);
    while (1) {
       int *connfdp = Malloc(sizeof(int));
       *connfdp = Accept(listenfd,
                         (SA *) &clientaddr, &clientlen);
       Pthread_create(&tid, NULL, echo_thread, connfdp);
    }
}
```

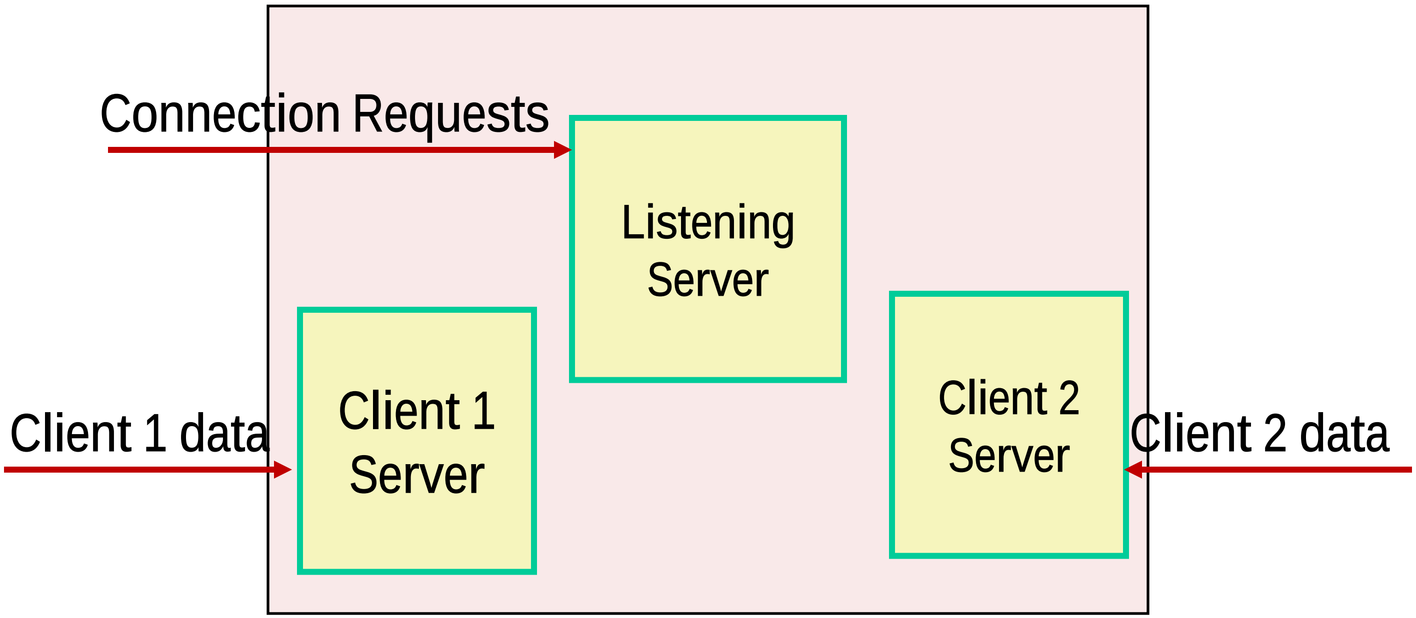
- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of Malloc()!
  - Without corresponding Free()

Thread-Based Concurrent Server (cont)

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

- Run thread in “detached” mode
  - Runs independently of other threads
  - Reaped automatically (by kernel) when it terminates
- Free storage allocated to hold clientfd
  - “Producer-Consumer” model

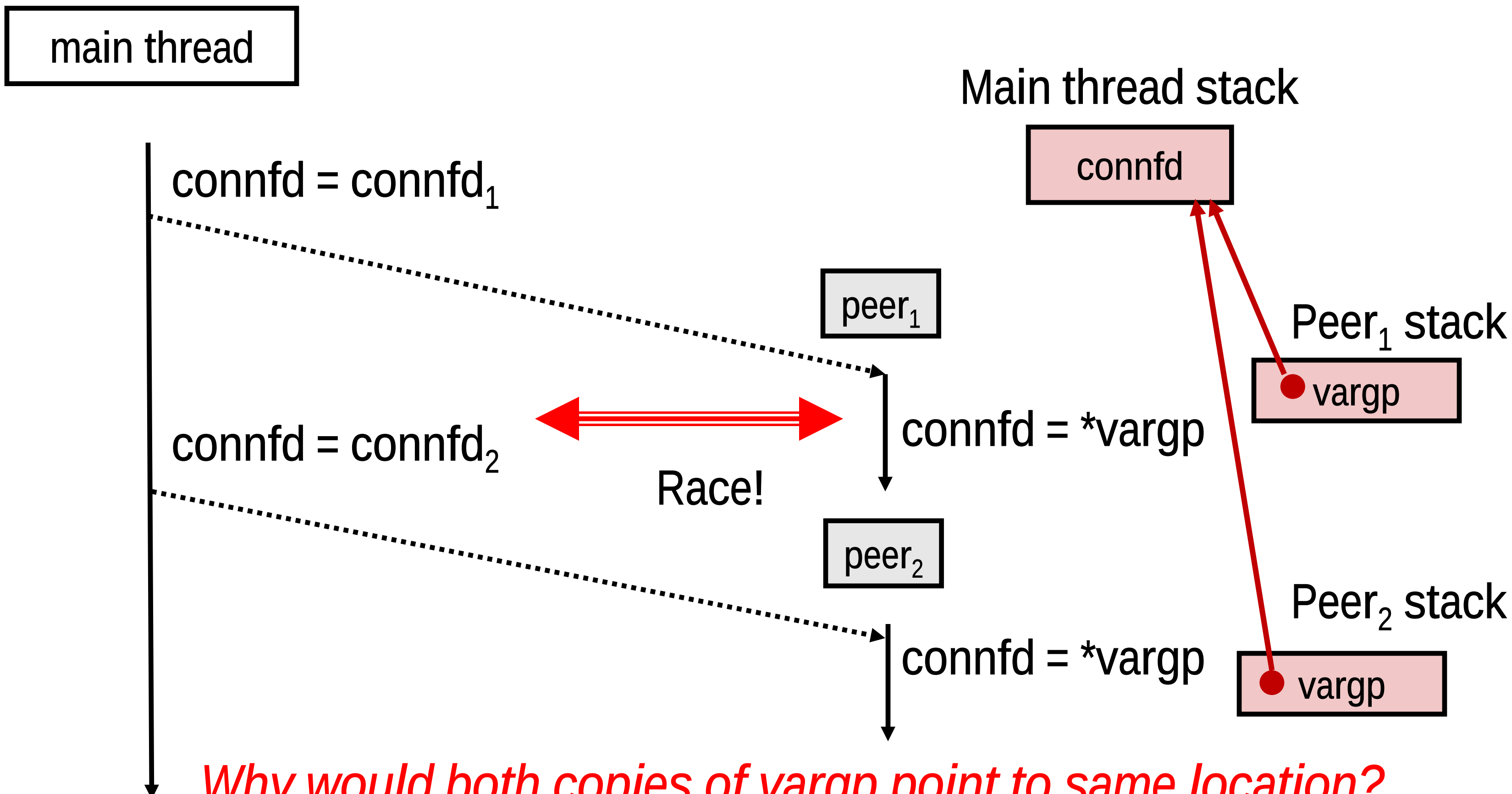
Threaded Execution Model



- Multiple threads within single process
- Some state between them
  - e.g., file descriptors

Potential Form of Unintended Sharing

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



Why would both copies of vargp point to same location?

Could this race occur?

Main

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

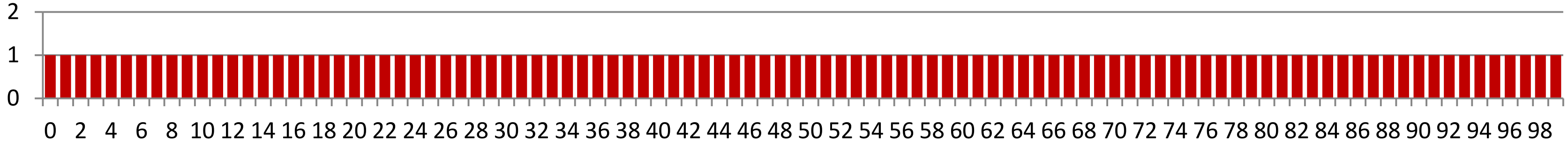
Thread

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

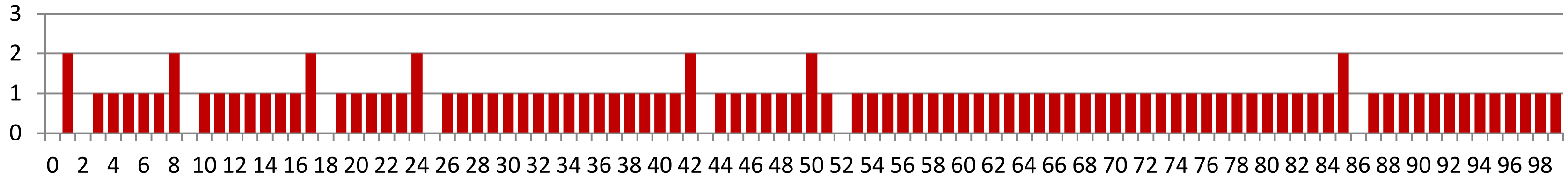
- **Race Test**
  - If no race, then each thread would get different value of i
  - Set of saved values would consist of one copy each of 0 through 99

Experimental Results

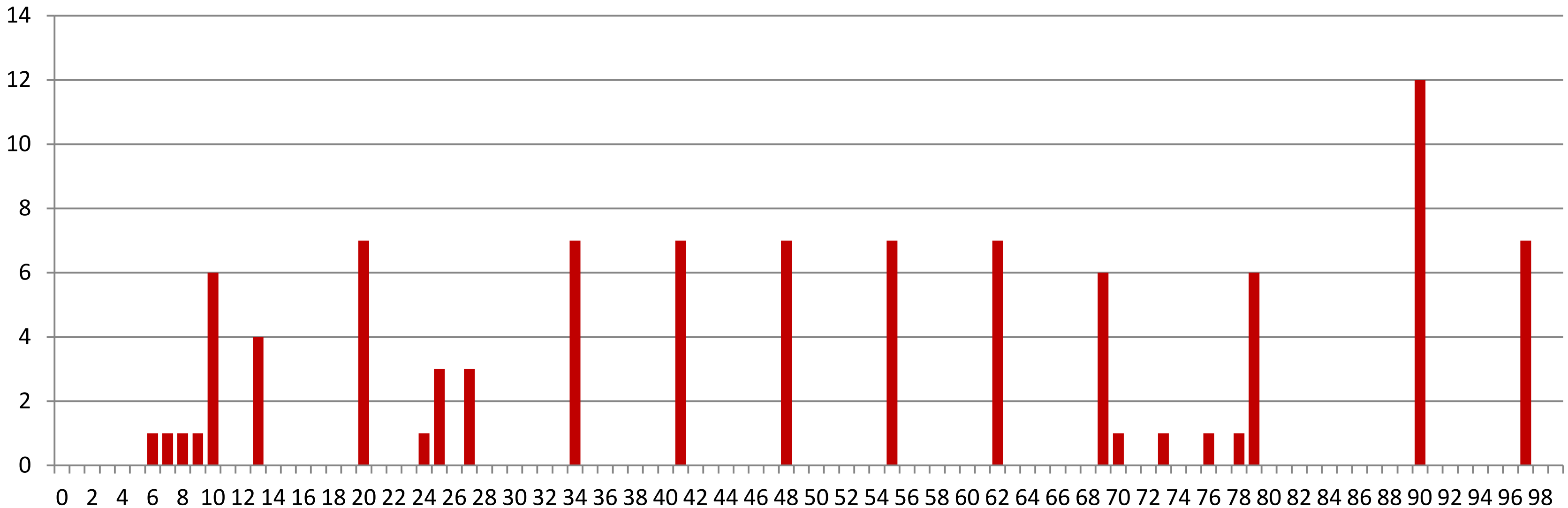
No Race



Single core laptop



Multicore server



- **The race can really happen!**

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)

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

Approaches to Concurrency

- **Processes**
  - Hard to share resources: Easy to avoid unintended sharing
  - High overhead in adding/removing clients
- **Threads**
  - Easy to share resources: Perhaps too easy
  - Medium overhead
  - Not much control over scheduling policies
  - Difficult to debug
    - Event orderings not repeatable
- **I/O Multiplexing**
  - 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

View from Server's TCP Manager

Client 1 **Client 2** **Server**

```
srv> ./echoserverp 15213
```

```
cl1> ./echoclient greatwhite.ics.cs.cmu.edu 15213
```

```
srv> connected to (128.2.192.34), port 50437
```

```
cl2> ./echoclient greatwhite.ics.cs.cmu.edu 15213
```

```
srv> connected to (128.2.205.225), port 41656
```

Connection	Host	Port	Host	Port
Listening	---	---	128.2.220.10	15213
cl1	128.2.192.34	50437	128.2.220.10	15213
cl2	128.2.205.225	41656	128.2.220.10	15213

View from Server's TCP Manager

Connection	Host	Port	Host	Port
Listening	---	---	128.2.220.10	15213
cl1	128.2.192.34	50437	128.2.220.10	15213
cl2	128.2.205.225	41656	128.2.220.10	15213

- **Port Demultiplexing**
  - TCP manager maintains separate stream for each connection
    - Each represented to application program as socket
    - New connections directed to listening socket
    - Data from clients directed to one of the connection sockets