

15-213

“The course that gives CMU its Zip!”

Concurrent Programming

April 24, 2008

Topics

- Limitations of iterative servers
- Process-based concurrent servers
- Threads-based concurrent servers
- Event-based concurrent servers

Concurrent Programming is Hard!

The human mind tends to be sequential

The notion of time is often misleading

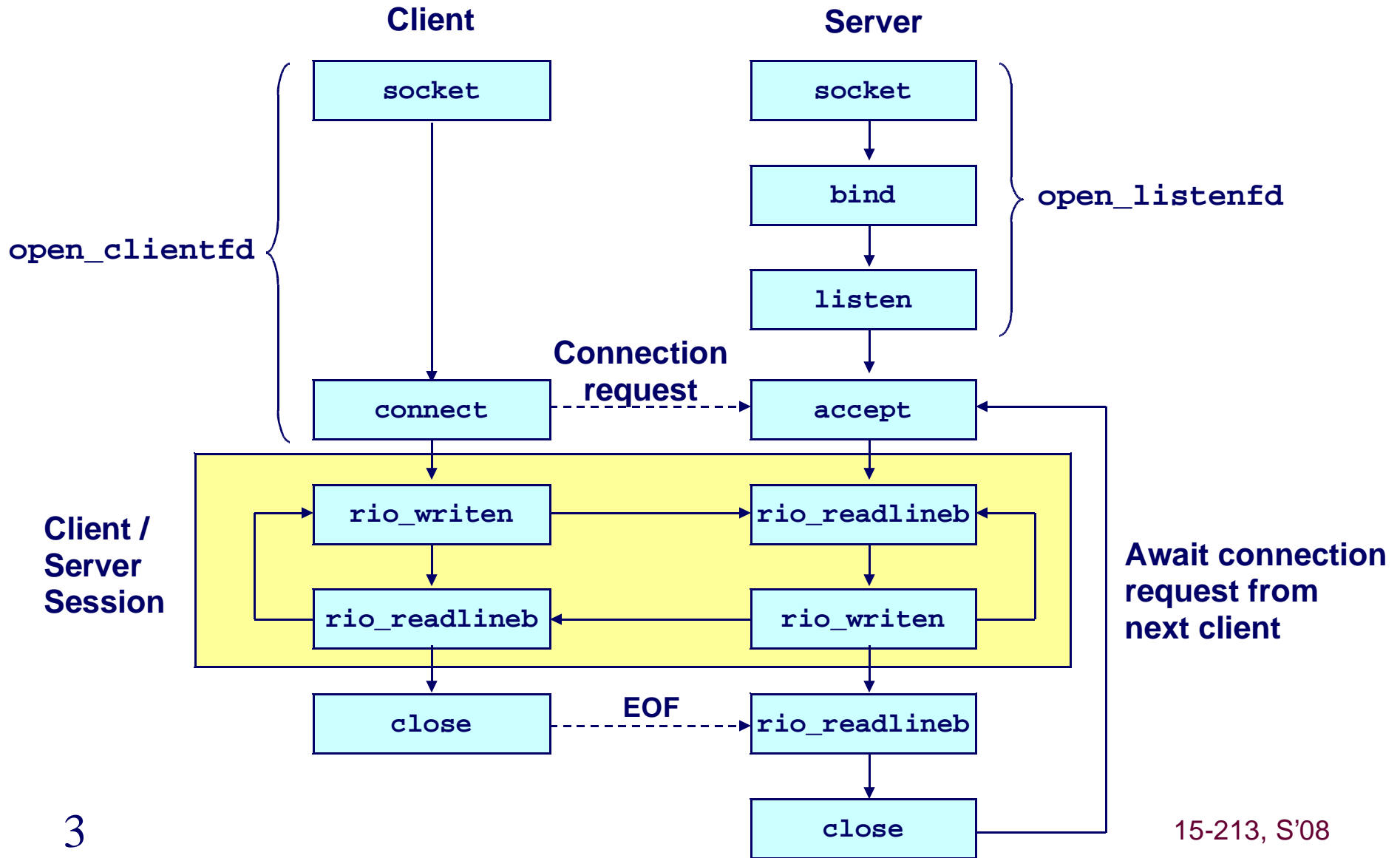
Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible

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**

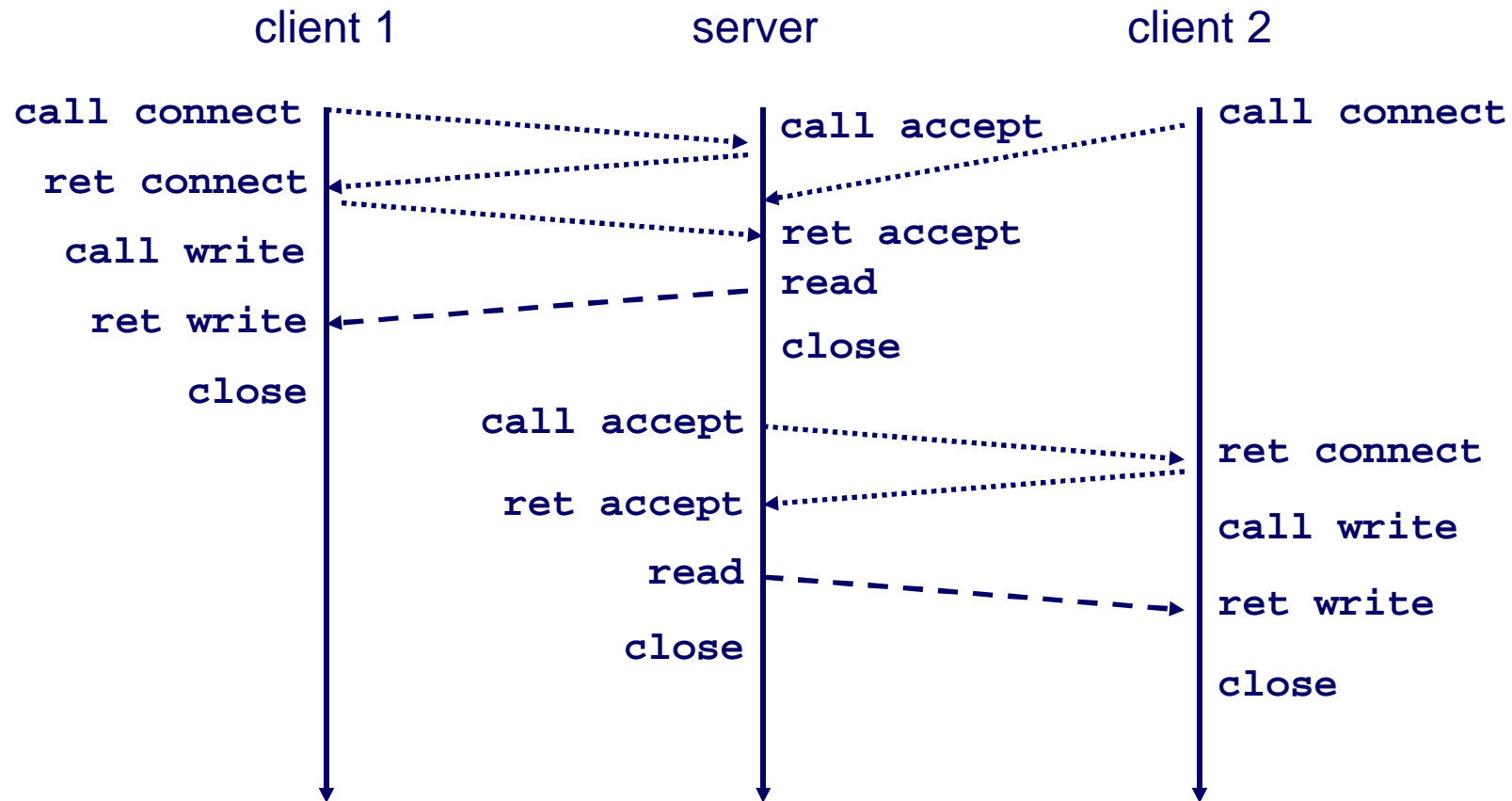
Many aspects of concurrent programming are beyond the scope of 15-213

Echo Server Operation

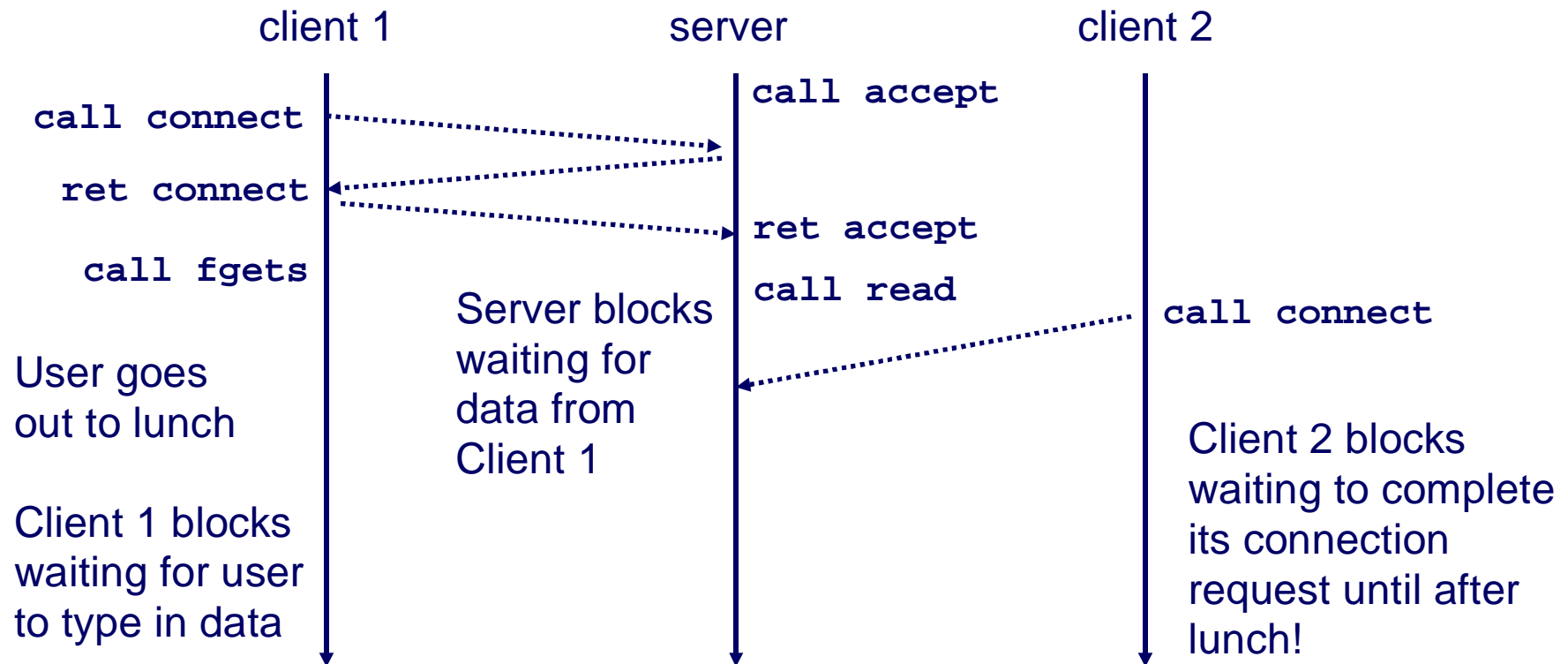


Iterative Servers

Iterative servers process one request at a time.



Fundamental Flaw of Iterative Servers

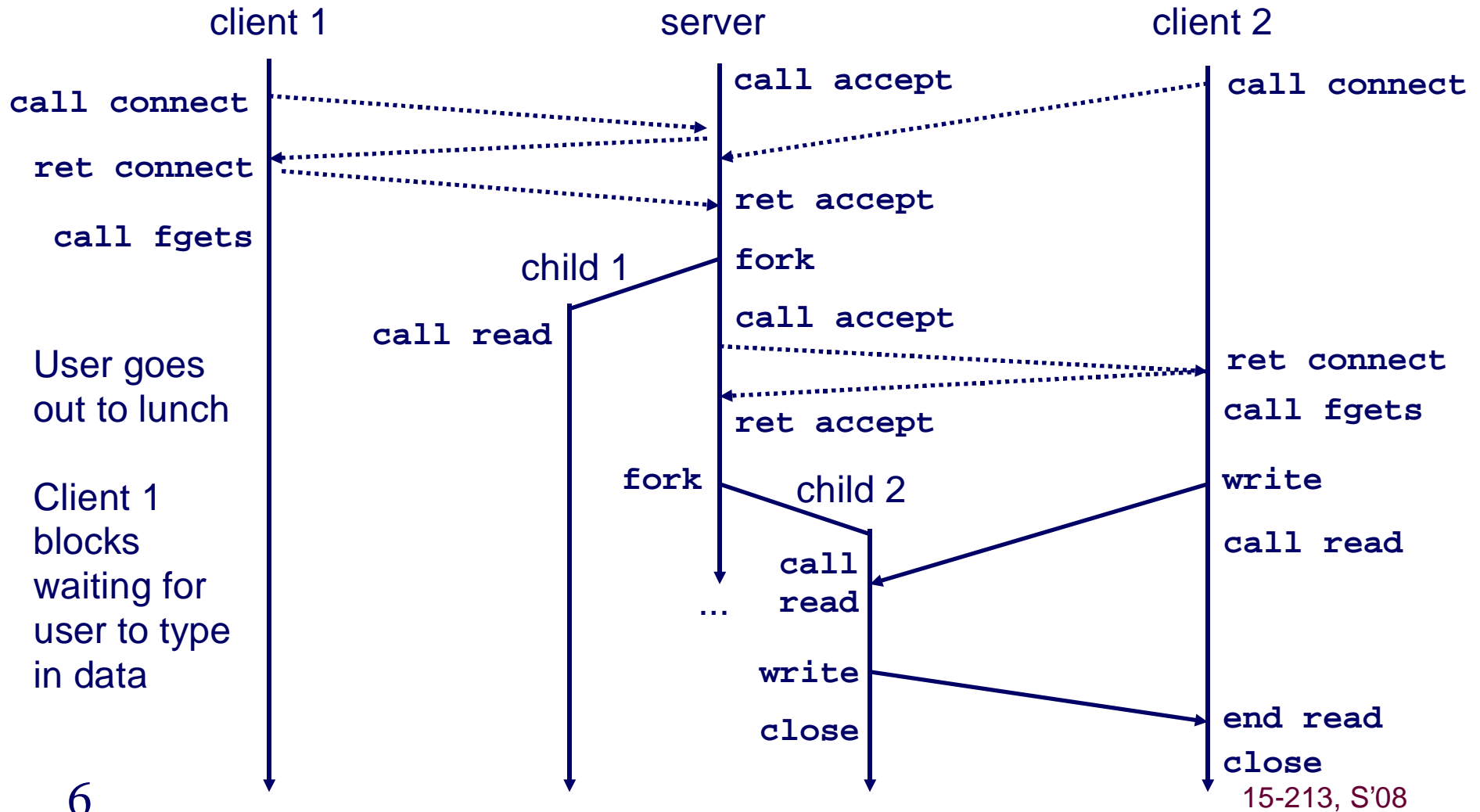


Solution: use *concurrent servers* instead.

- **Concurrent servers use multiple concurrent flows to serve multiple clients at the same time.**

Concurrent Servers: Multiple Processes

Concurrent servers handle multiple requests concurrently.



Three Basic Mechanisms for Creating Concurrent Flows

1. Processes

- Kernel automatically interleaves multiple logical flows.
- Each flow has its own private address space.

2. Threads

- Kernel automatically interleaves multiple logical flows.
- All flows share the same address space.

3. I/O multiplexing with `select()`

- Programmer manually interleaves multiple logical flows.
- All flows share the same address space.
- Popular for high-performance server designs.

Review: Sequential 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**

Inner Echo Loop

```
void echo(int connfd)
{
    size_t n;
    char buf[MAXLINE];
    rio_t rio;

    Rio_readinitb(&rio, connfd);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", n);
        Rio_writen(connfd, buf, n);
    }
}
```

- Server reads lines of text
- Echos them right back

Echo Server: `accept` Illustrated



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



2. Client makes connection request by calling and blocking in `connect()`.



3. Server receives `connfd` from `accept()`. Client returns from `connect()`. Connection is now established between `clientfd` and `connfd`.

Process-Based Concurrent 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!) */
    }
}
```

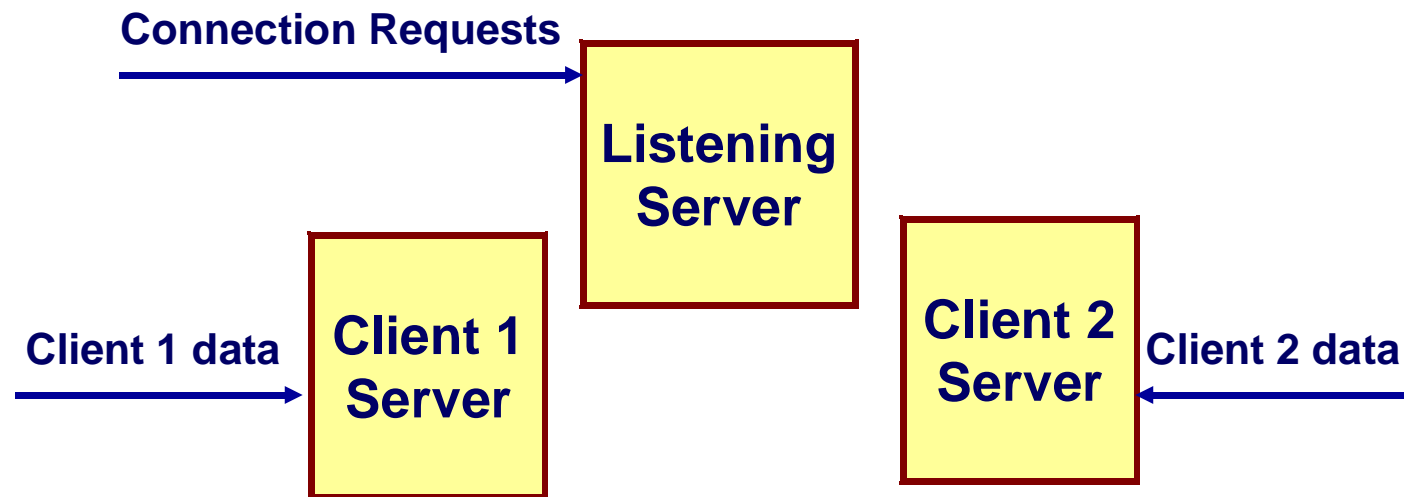
Fork separate process for each client
Does not allow any communication between different client handlers

Process-Based Concurrent 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
- When child created, each has copies of `listenfd` and `connfd`
 - Parent must close `connfd`, child must close `listenfd`

Implementation Issues With Process-Based Designs

Server must reap zombie children

- to avoid fatal memory leak.

Server 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`.

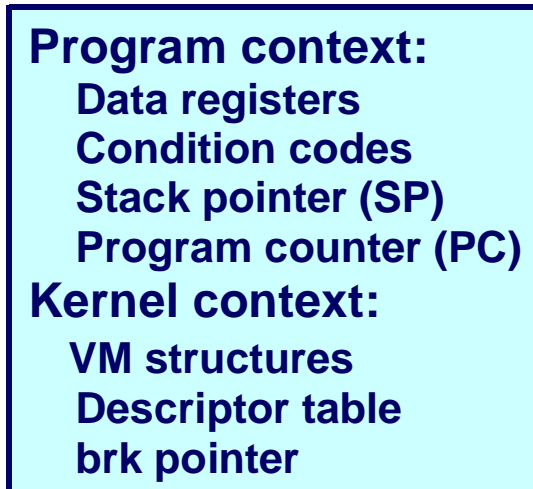
Pros and Cons of Process-Based Designs

- + Handles 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

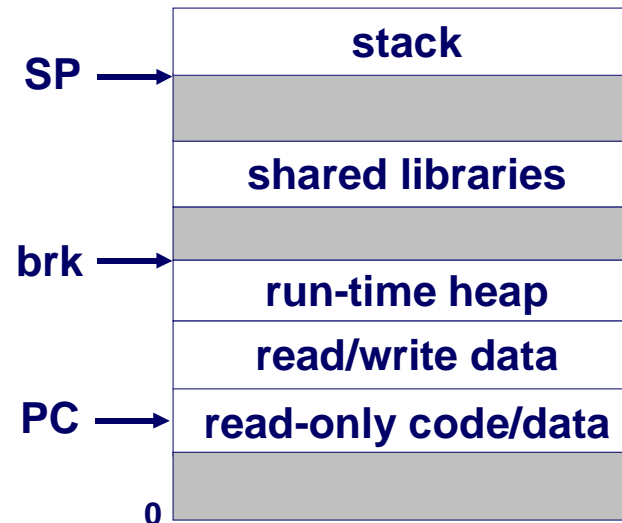
Traditional View of a Process

Process = process context + code, data, and stack

Process context

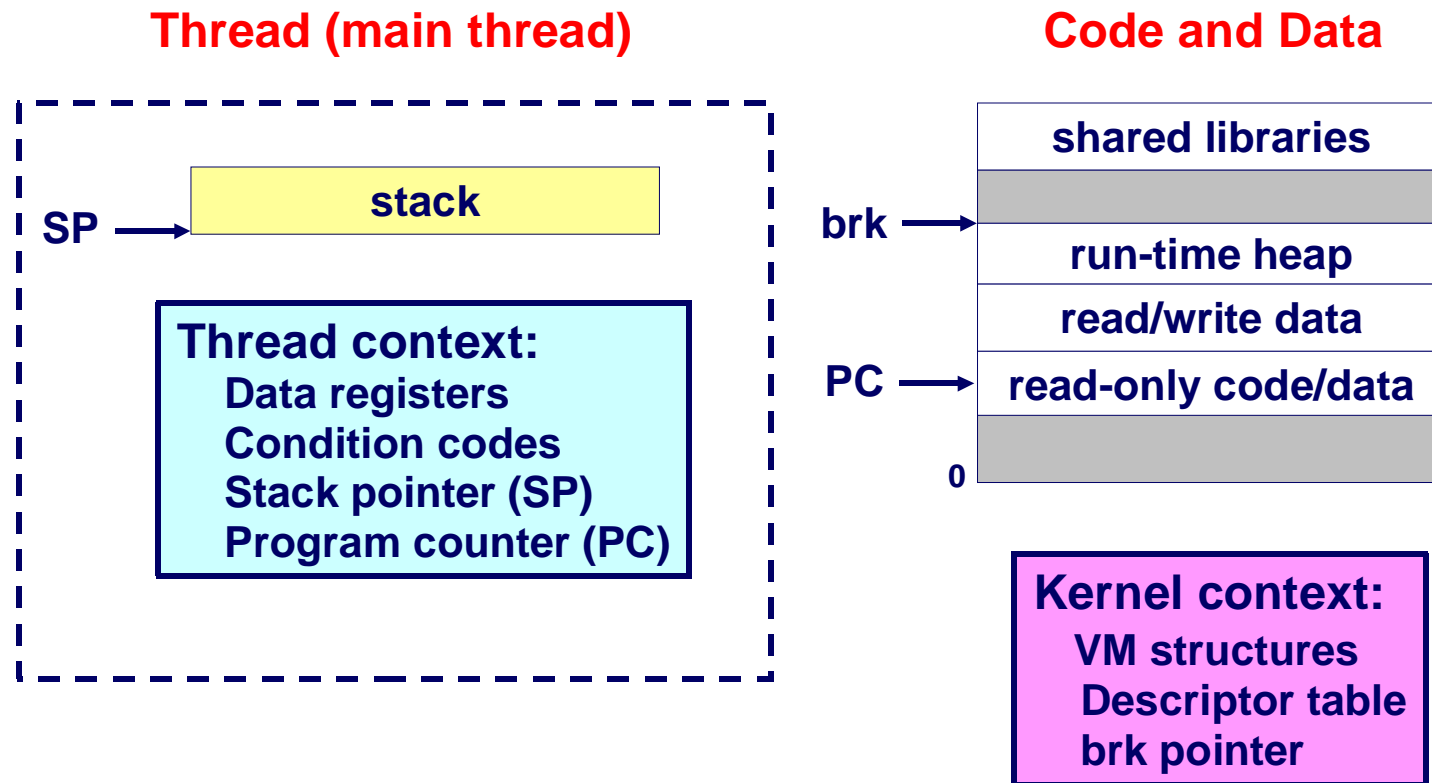


Code, data, and stack



Alternate View of a Process

Process = thread + code, data, and kernel context



A Process With Multiple Threads

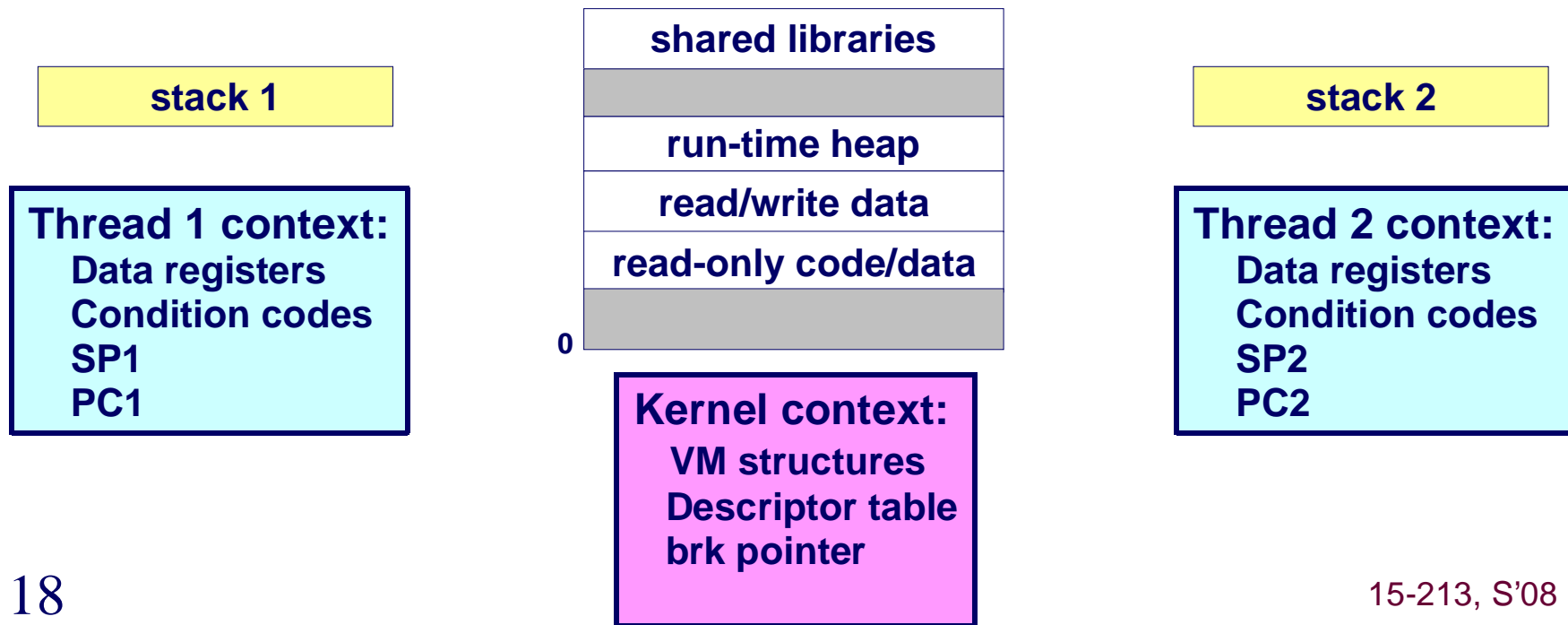
Multiple threads can be associated with a process

- Each thread has its own logical control flow
- Each thread shares the same code, data, and kernel context
 - Share common virtual address space
- Each thread has its own thread id (TID)

Thread 1 (main thread)

Shared code and data

Thread 2 (peer thread)

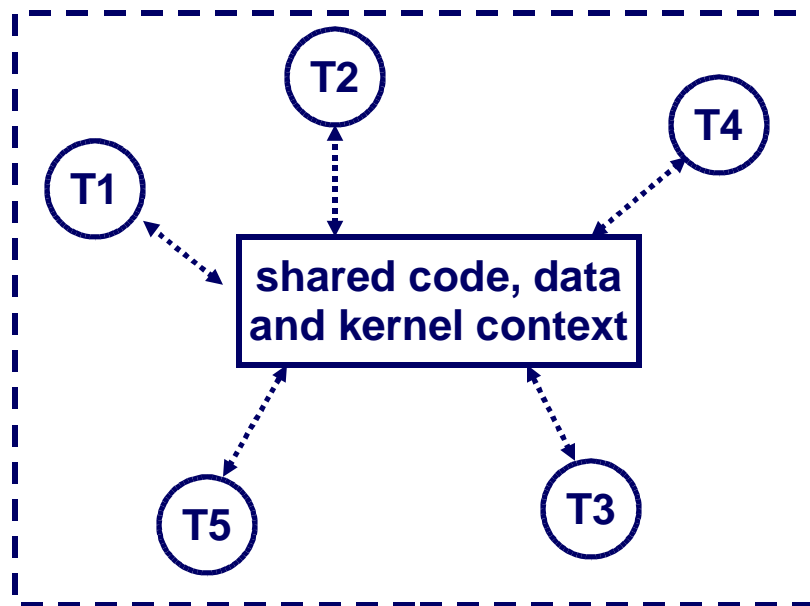


Logical View of Threads

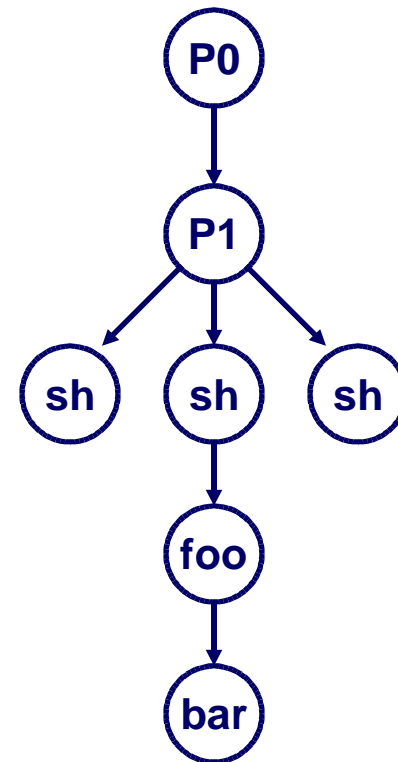
Threads associated with process form a pool of peers.

- Unlike processes which form a tree hierarchy

Threads associated with process foo



Process hierarchy



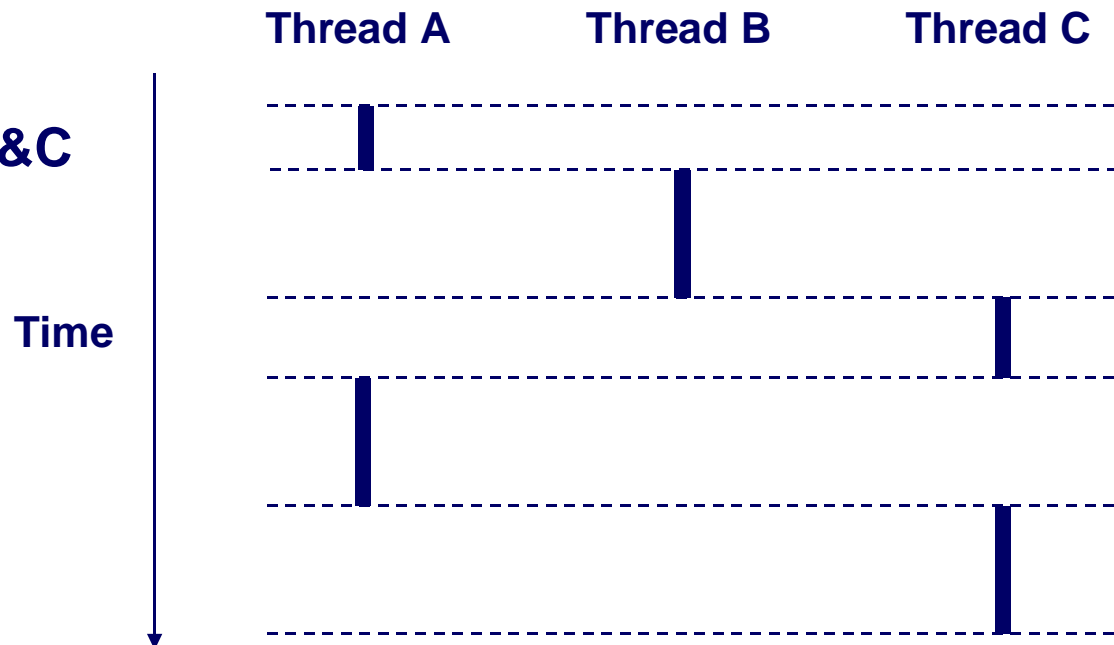
Concurrent Thread Execution

Two threads run concurrently (are concurrent) if their logical 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.
- Each is context switched.

How threads and processes are different

- Threads share code and data, processes (typically) do not.
- Threads are somewhat less expensive than processes.
 - Process control (creating and reaping) is twice as expensive as thread control.
 - Linux/Pentium III numbers:
 - ~20K cycles to create and reap a process.
 - ~10K cycles 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);
}

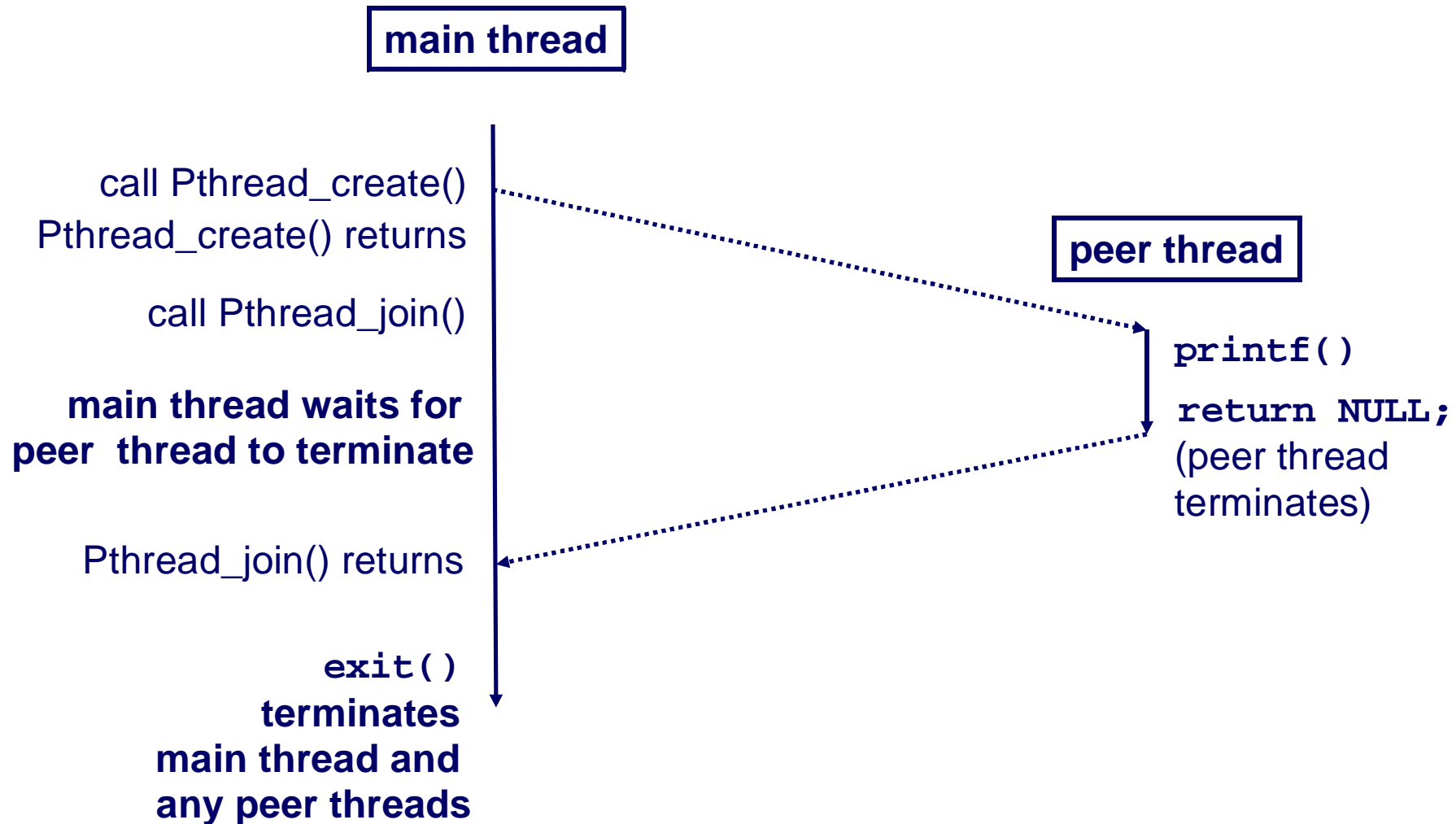
/* thread routine */
void *thread(void *vargp) {
    printf("Hello, world!\n");
    return NULL;
}
```

*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);
    }
}
```

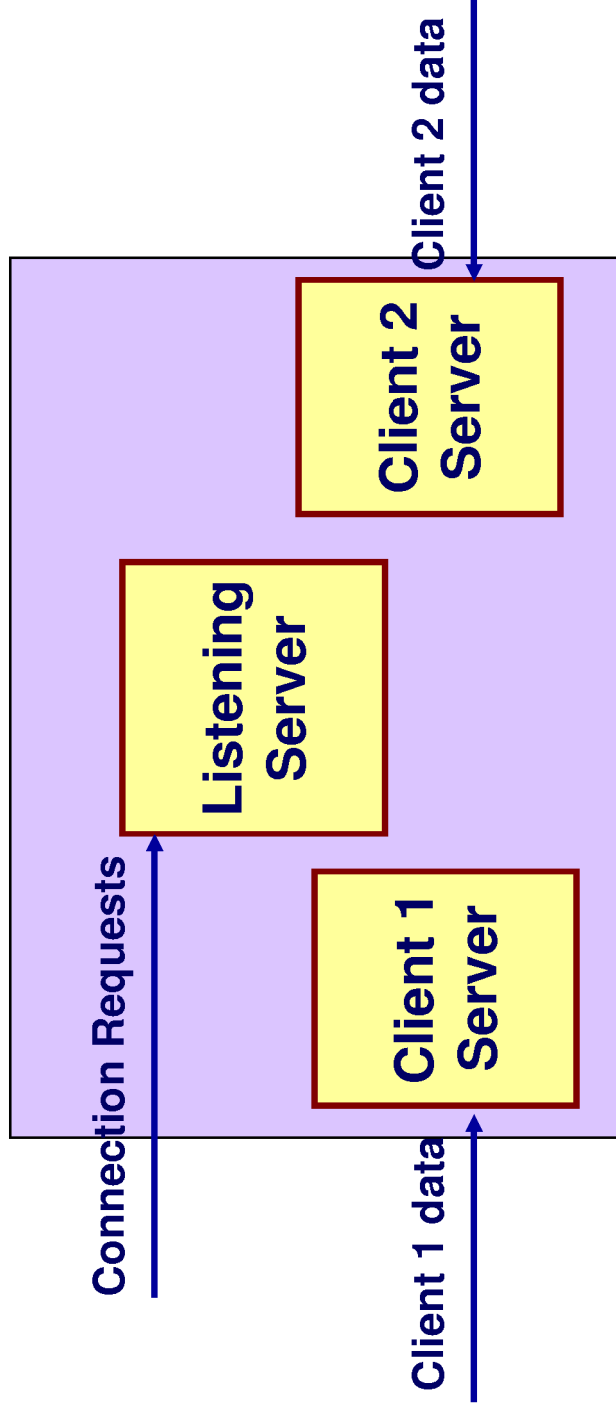
- **Spawn new thread for each client**
- **Pass it copy of connection file descriptor**
- **Note use of Malloc()!**
 - **Without corresponding Free()**

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 when it terminates
- Free storage allocated to hold clientfd
 - “Producer-Consumer” model

Threaded-Process Execution Model

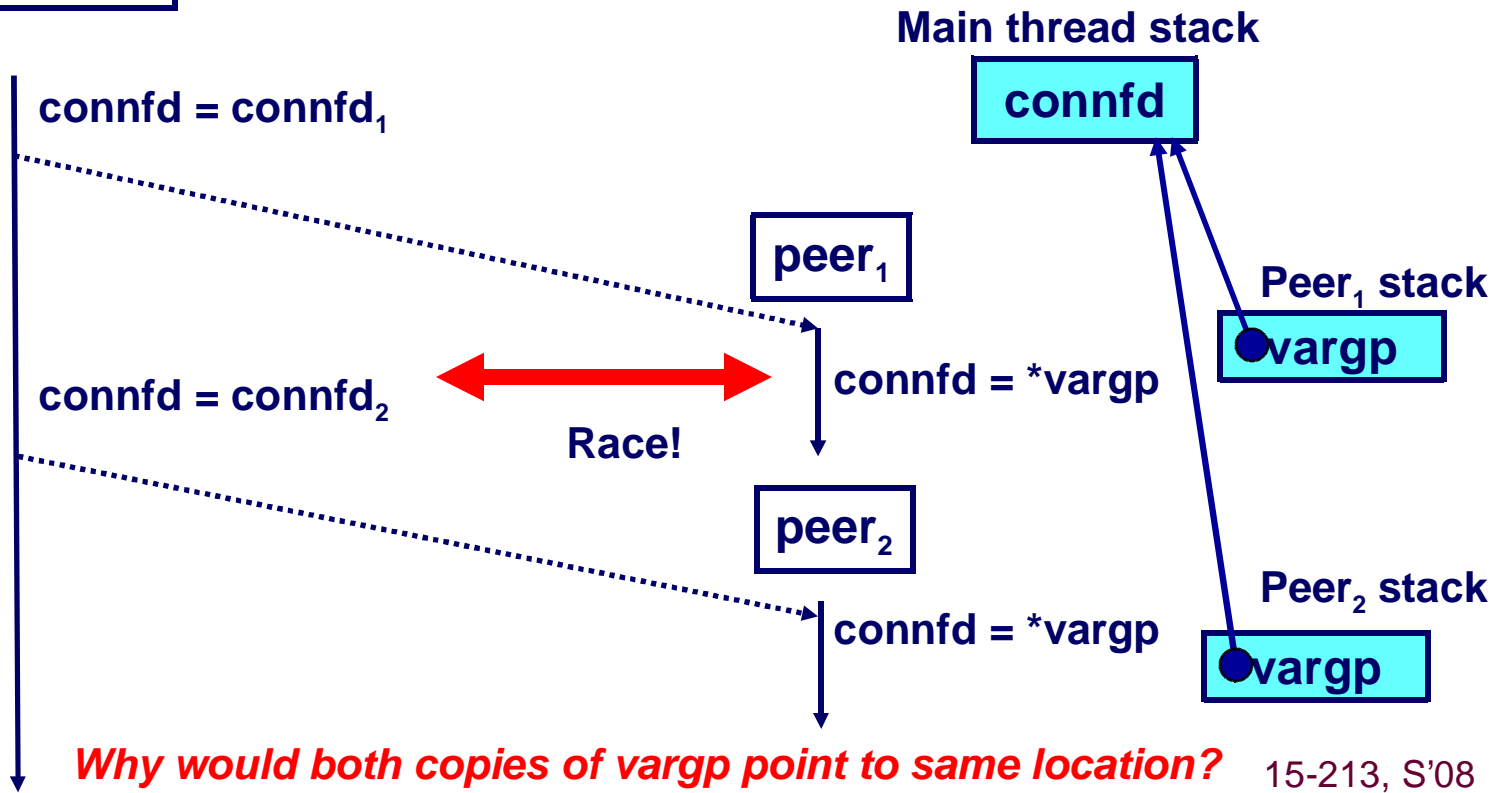


- Multiple threads within single process
- Some state between them
 - File descriptors (in this example; usually more)

Potential Form of Unintended Sharing

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

main thread



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, what happens if we pass the address of `connfd` to the thread routine?
 - `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.
- (next lecture)

Event-Based Concurrent Servers Using I/O Multiplexing

Maintain a pool of connected descriptors.

Repeat the following forever:

- Use the Unix `select()` function to block until:
 - (a) New connection request arrives on the listening descriptor.
 - (b) New data arrives on an existing connected descriptor.
- If (a), add the new connection to the pool of connections.
- If (b), read any available data from the connection
 - Close connection on EOF and remove it from the pool.

The `select()` Function

`select()` sleeps until one or more file descriptors in the set `readset` ready for reading.

```
#include <sys/select.h>

int select(int maxfdp1, fd_set *readset, NULL, NULL, NULL);
```

`readset`

- Opaque bit vector (max `FD_SETSIZE` bits) that indicates membership in a *descriptor set*.
- If bit `k` is 1, then descriptor `k` is a member of the descriptor set.

`maxfdp1`

- Maximum descriptor in descriptor set plus 1.
- Tests descriptors 0, 1, 2, ..., `maxfdp1 - 1` for set membership.

`select()` returns the number of ready descriptors and sets each bit of `readset` to indicate the ready status of its corresponding descriptor.

Macros for Manipulating Set Descriptors

```
void FD_ZERO(fd_set *fdset);
```

- Turn off all bits in `fdset`.

```
void FD_SET(int fd, fd_set *fdset);
```

- Turn on bit `fd` in `fdset`.

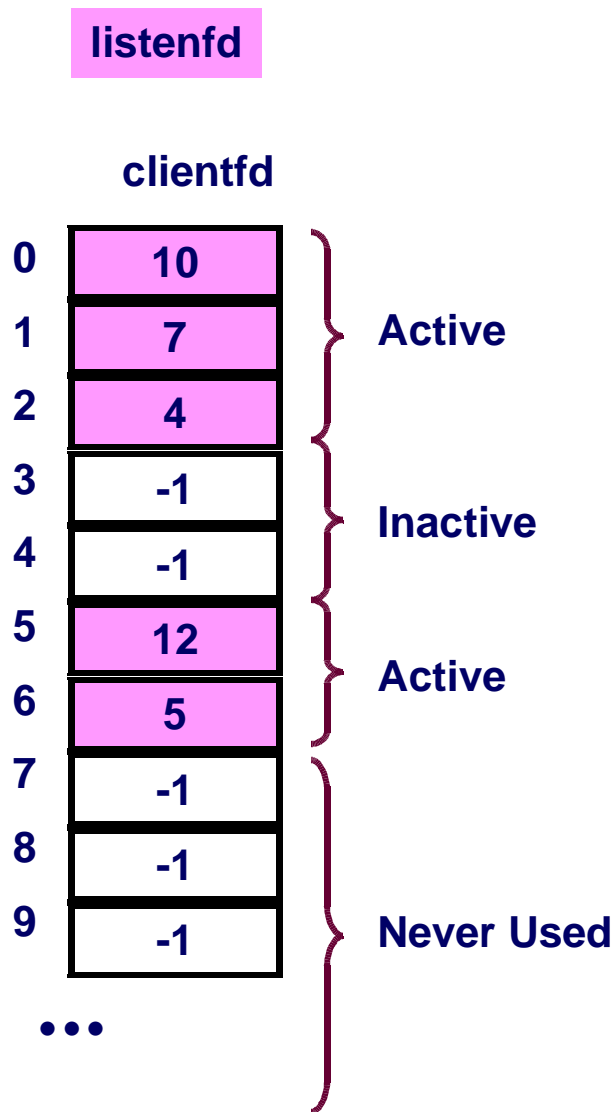
```
void FD_CLR(int fd, fd_set *fdset);
```

- Turn off bit `fd` in `fdset`.

```
int FD_ISSET(int fd, *fdset);
```

- Is bit `fd` in `fdset` turned on?

Overall Structure



Manage Pool of Connections

- listenfd: Listen for requests from new clients
- Active clients: Ones with a valid connection

Use select to detect activity

- New request on listenfd
- Request by active client

Required Activities

- Adding new clients
- Removing terminated clients
- Echoing

Representing Pool of Clients

```
/*
 * echoservers.c - A concurrent echo server based on select
 */
#include "csapp.h"

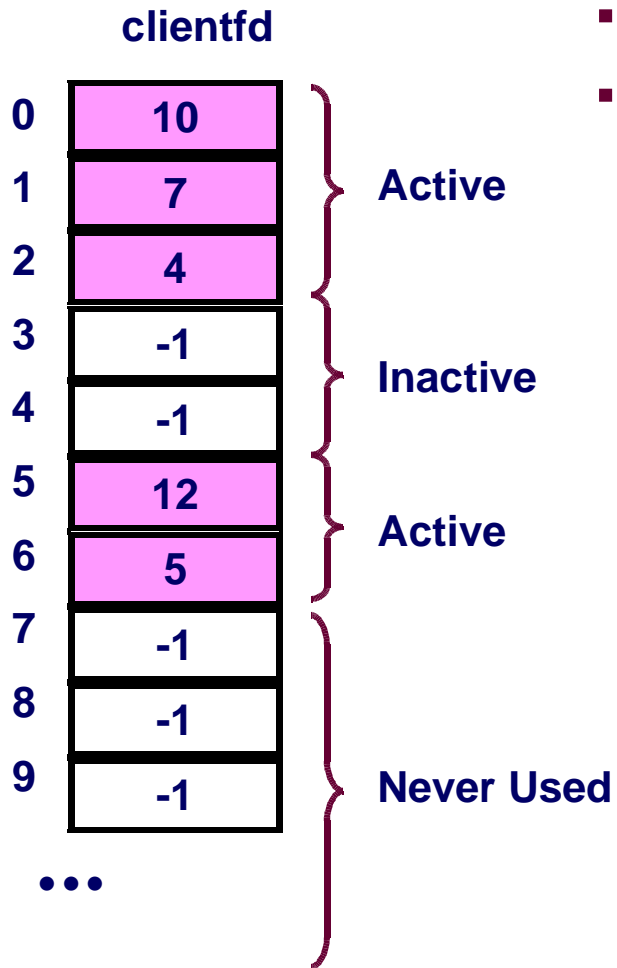
typedef struct { /* represents a pool of connected descriptors */
    int maxfd;          /* largest descriptor in read_set */
    fd_set read_set;   /* set of all active descriptors */
    fd_set ready_set; /* subset of descriptors ready for reading */
    int nready;        /* number of ready descriptors from select */

    int maxi;          /* highwater index into client array */
    int clientfd[FD_SETSIZE]; /* set of active descriptors */
    rio_t clientrio[FD_SETSIZE]; /* set of active read buffers */
} pool;

int byte_cnt = 0; /* counts total bytes received by server */
```

Pool Example

listenfd = 3



- maxfd = 12
- maxi = 6
- read_set = { 3, 4, 5, 7, 10, 12 }

Main Loop

```
int main(int argc, char **argv)
{
    int listenfd, connfd, clientlen = sizeof(struct sockaddr_in);
    struct sockaddr_in clientaddr;
    static pool pool;

    listenfd = Open_listenfd(argv[1]);
    init_pool(listenfd, &pool);

    while (1) {
        pool.ready_set = pool.read_set;
        pool.nready = Select(pool.maxfd+1, &pool.ready_set,
                            NULL, NULL, NULL);

        if (FD_ISSET(listenfd, &pool.ready_set)) {
            connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
            add_client(connfd, &pool);
        }
        check_clients(&pool);
    }
}
```

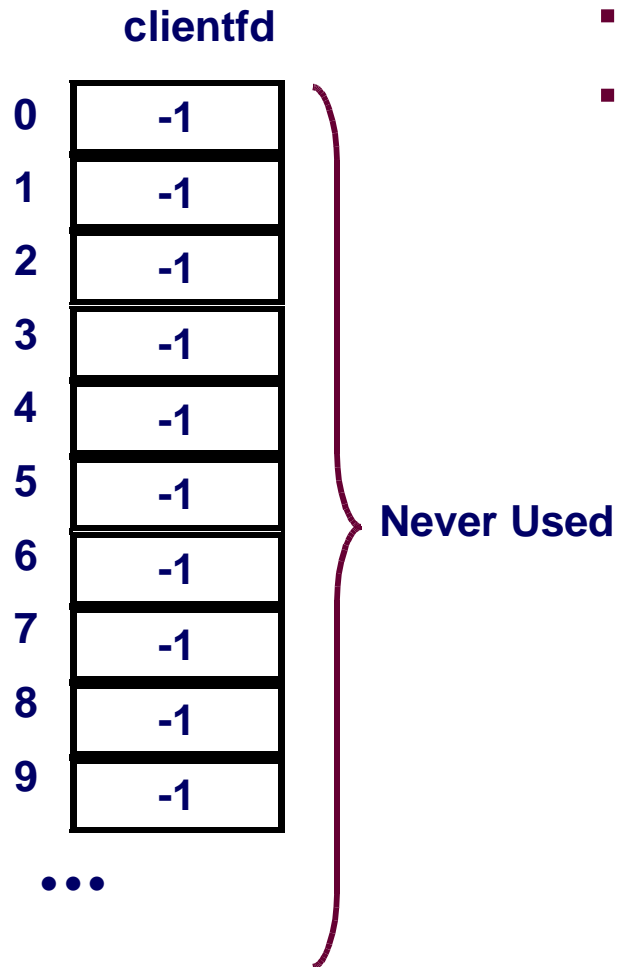
Pool Initialization

```
/* initialize the descriptor pool */
void init_pool(int listenfd, pool *p)
{
    /* Initially, there are no connected descriptors */
    int i;
    p->maxi = -1;
    for (i=0; i< FD_SETSIZE; i++)
        p->clientfd[i] = -1;

    /* Initially, listenfd is only member of select read set */
    p->maxfd = listenfd;
    FD_ZERO(&p->read_set);
    FD_SET(listenfd, &p->read_set);
}
```

Initial Pool

listenfd = 3



- maxfd = 3
- maxi = -1
- read_set = { 3 }

Adding Client

```
void add_client(int connfd, pool *p) /* add connfd to pool p */
{
    int i;
    p->nready--;

    for (i = 0; i < FD_SETSIZE; i++) /* Find available slot */
        if (p->clientfd[i] < 0) {
            p->clientfd[i] = connfd;
            Rio_readinitb(&p->clientrio[i], connfd);

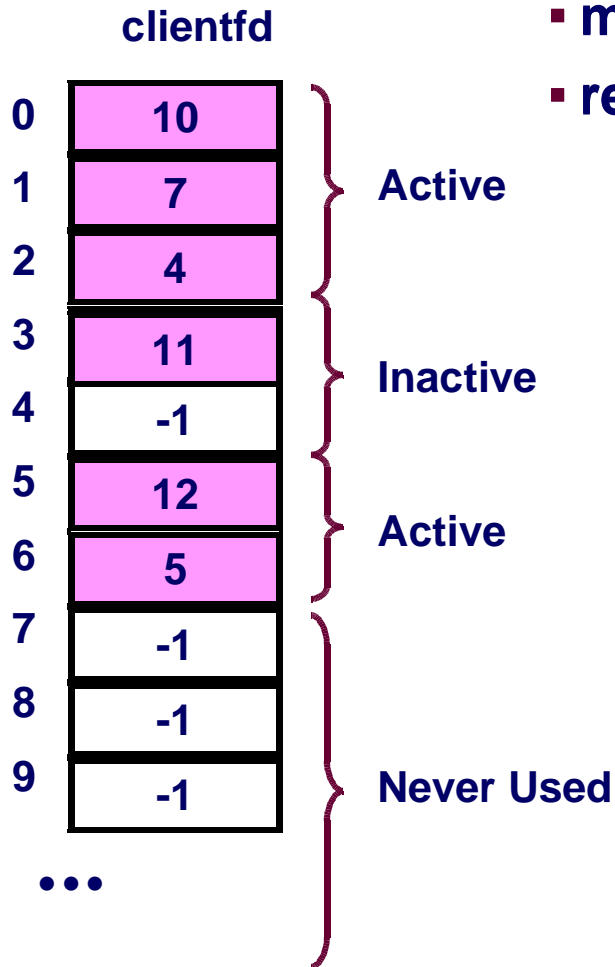
            FD_SET(connfd, &p->read_set); /* Add desc to read set */

            if (connfd > p->maxfd) /* Update max descriptor num */
                p->maxfd = connfd;
            if (i > p->maxi) /* Update pool high water mark */
                p->maxi = i;
            break;
        }
    if (i == FD_SETSIZE) /* Couldn't find an empty slot */
        app_error("add_client error: Too many clients");
}
```


Adding Client with fd 11

listenfd = 3

- maxfd = 12
- maxi = 6
- read_set = { 3, 4, 5, 7, 10, 11, 12 }



Checking Clients

```
void check_clients(pool *p) { /* echo line from ready descs in pool p */
    int i, connfd, n;
    char buf[MAXLINE];
    rio_t rio;

    for (i = 0; (i <= p->maxi) && (p->nready > 0); i++) {
        connfd = p->clientfd[i];
        rio = p->clientrio[i];

        /* If the descriptor is ready, echo a text line from it */
        if ((connfd > 0) && (FD_ISSET(connfd, &p->ready_set))) {
            p->nready--;
            if ((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
                byte_cnt += n;
                Rio_writen(connfd, buf, n);
            }
            else { /* EOF detected, remove descriptor from pool */
                Close(connfd);
                FD_CLR(connfd, &p->read_set);
                p->clientfd[i] = -1;
            }
        }
    }
}
```

Concurrency Limitations

```
if ((connfd > 0) && (FD_ISSET(connfd, &p->ready_set))) {  
    p->nready--;  
    if ((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {  
        byte_cnt += n;  
        Rio_writen(connfd, buf, n);  
    }  
}
```

Does not return until
complete line received

- Current design will hang up if partial line transmitted
- Bad to have network code that can hang up if client does something weird
 - By mistake or maliciously
- Would require more work to implement more robust version
 - Must allow each read to return only part of line, and reassemble lines within server

Pro and Cons of Event-Based Designs

- + One logical control flow.**
- + Can single-step with a debugger.**
- + No process or thread control overhead.**
 - Design of choice for high-performance Web servers and search engines.
- Significantly more complex to code than process- or thread-based designs.**
- Hard to provide fine-grained concurrency**
 - E.g., our example will hang up with partial lines.

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