# Programming for Concurrency

15-213/18-243: Introduction to Computer Systems

25th Lecture, 22 April 2010

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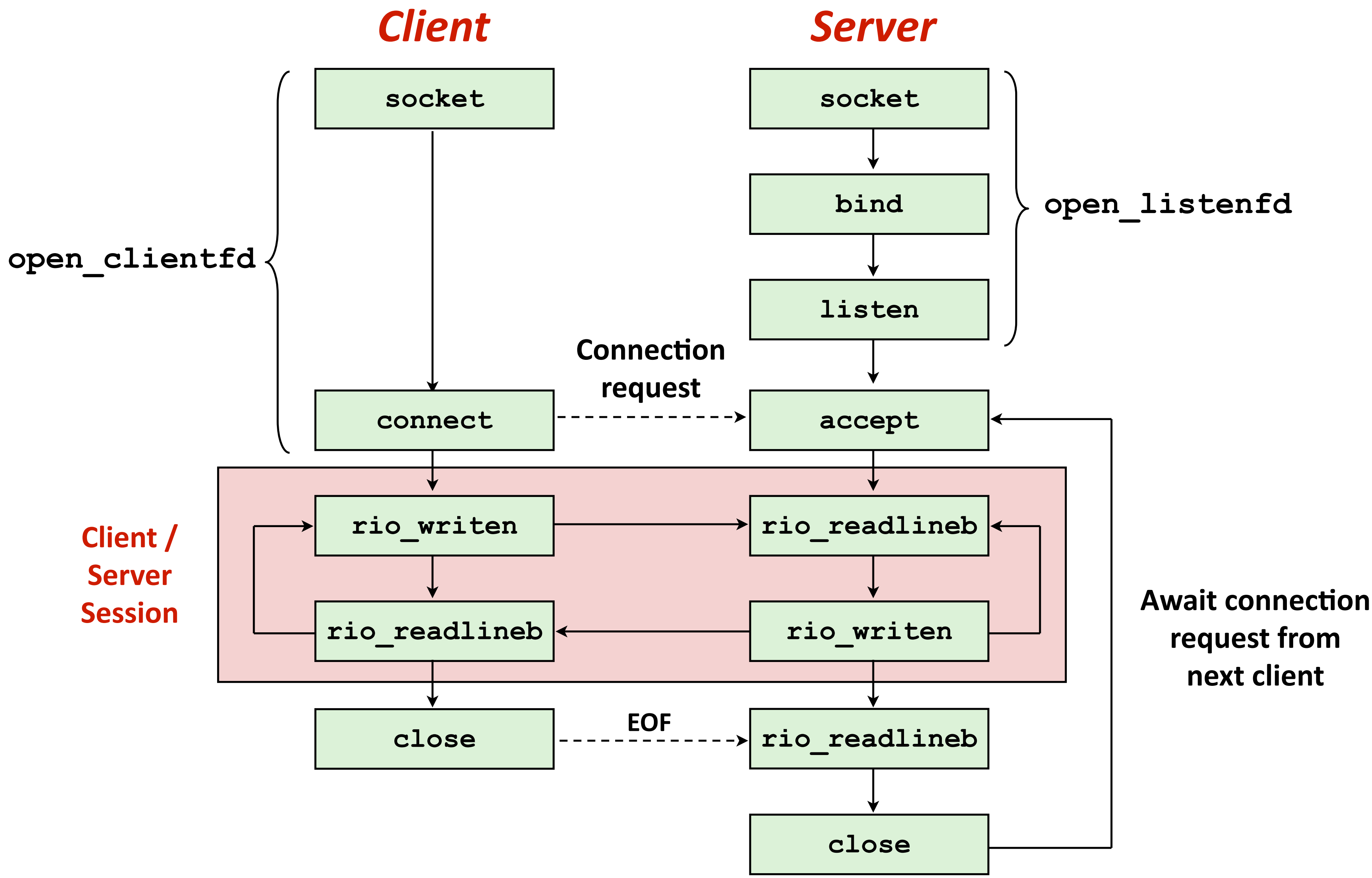
# Today

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

# Concurrent Programming is Hard!

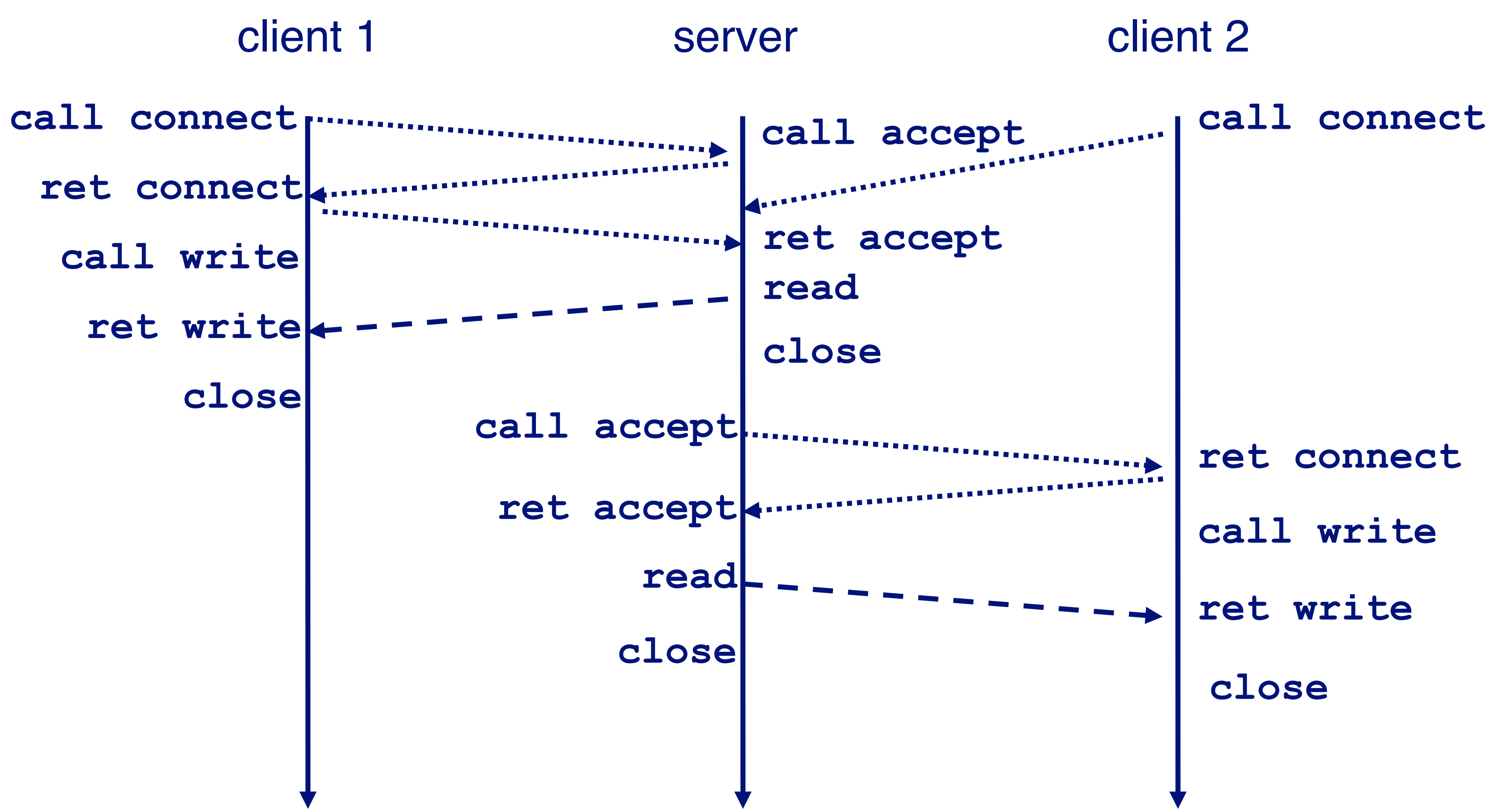
- **The human mind tends to be sequential**
- **The notion of time is often misleading**
- **Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible**
- **Classical problem classes of concurrent programs:**
  - ***Races:*** outcome depends 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 are beyond the scope of 15-213 / 18-243**

# Echo Server Operation

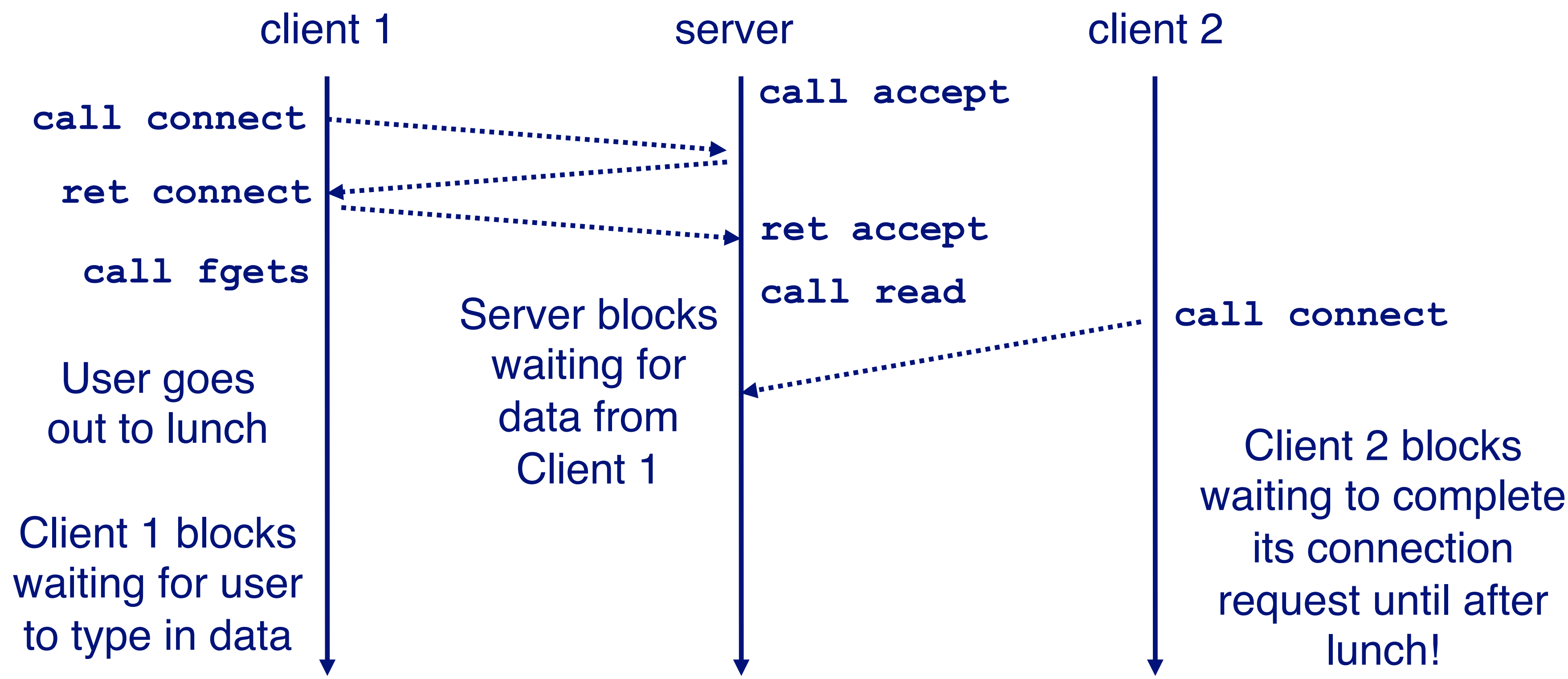


# Iterative Servers

- **Iterative servers process one request at a time.**

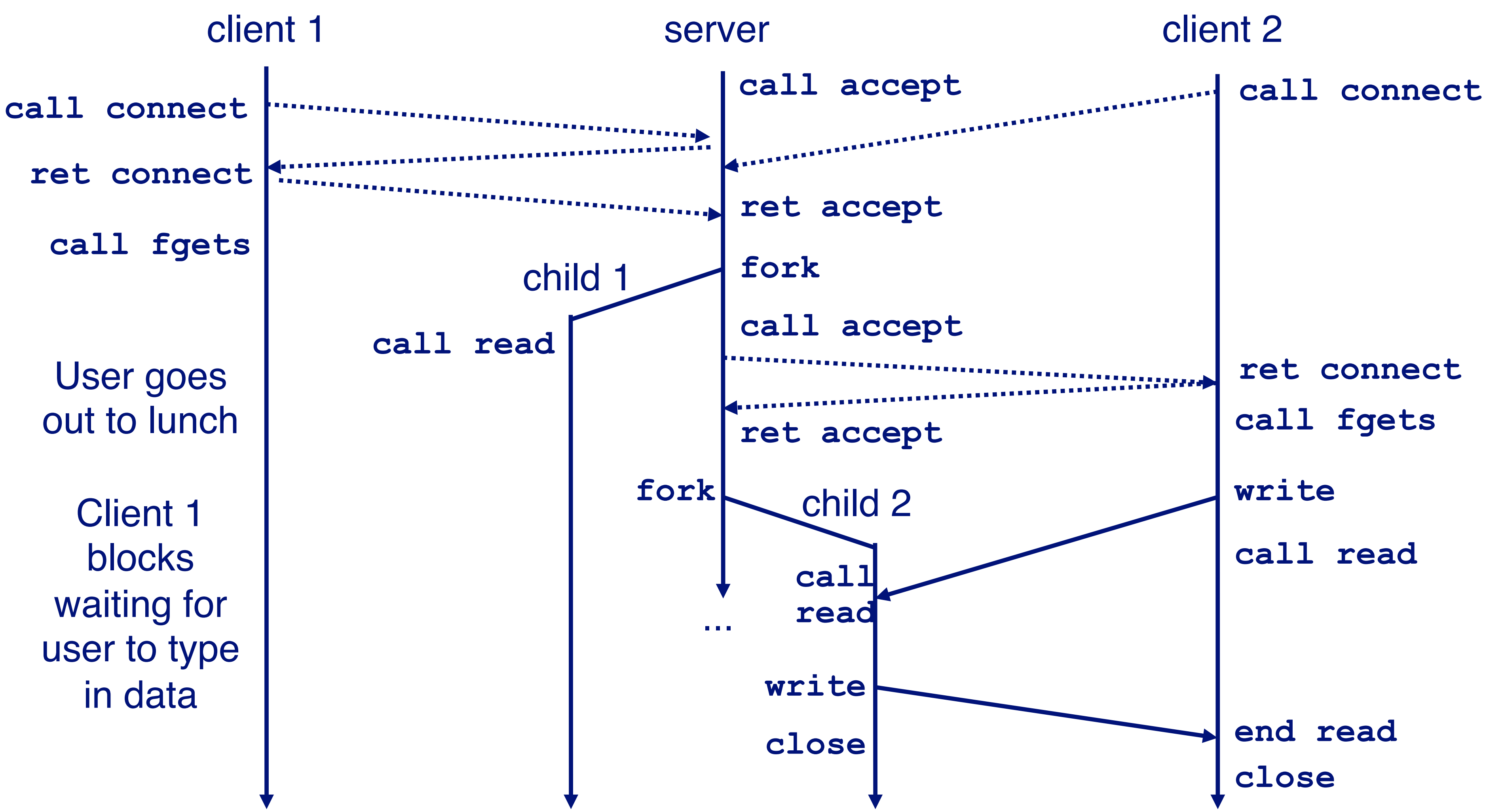


# Fundamental Flaw of Iterative Servers




- **Solution: use concurrent servers instead**
  - Multiple concurrent flows to serve multiple clients at the same time

# Concurrent Servers: Multiple Processes



# 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);
}
```

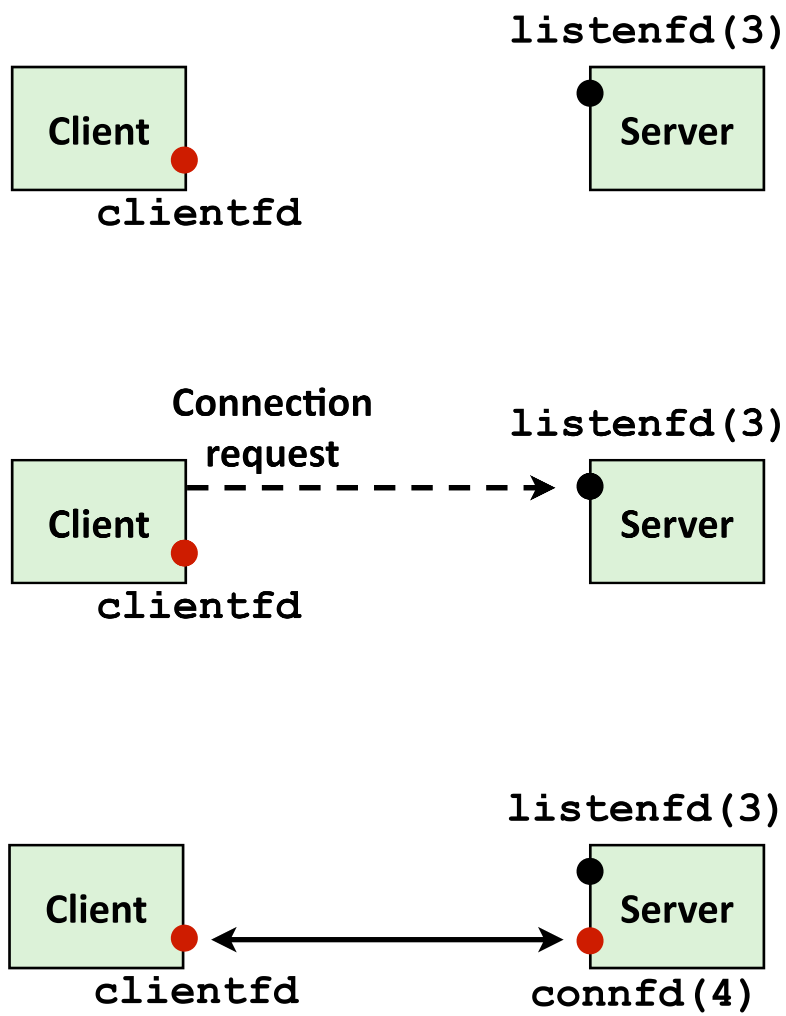
- Accept a connection request
- Handle echo requests until client terminates

# 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**
  - **`printf`**s a status statement for each

# 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 returns* `connfd` *from* `accept`. *Client returns from* `connect`. *Connection is now established between* `clientfd` *and* `connfd`

# Today

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

# 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!) */
  }
}
```

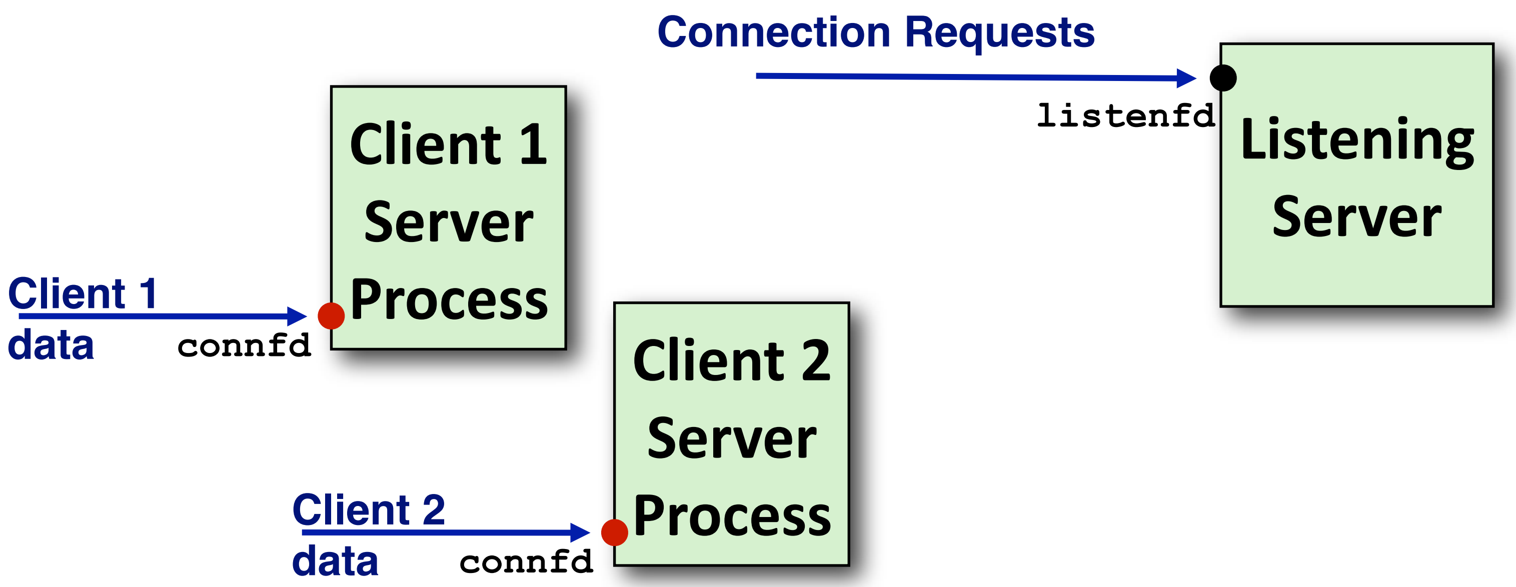
- Server forks a separate process to deal with each client
- No communication between child processes

# Process-Based Concurrent Server (cont'd)

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

- SIGCHLD is sent to a process when a child process terminates
- Parent must reap all zombie children

# Process Execution Model




- Each client handled by independent process
- No shared state between them
- When child created, each has copy of `listenfd` and `connfd`
  - Parent must close `connfd`, child must close `listenfd`

# Implementation Issues

- **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`**, reference count on **`connfd`** is 2
  - Connection will not be closed until reference count is zero

# 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

# Today

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

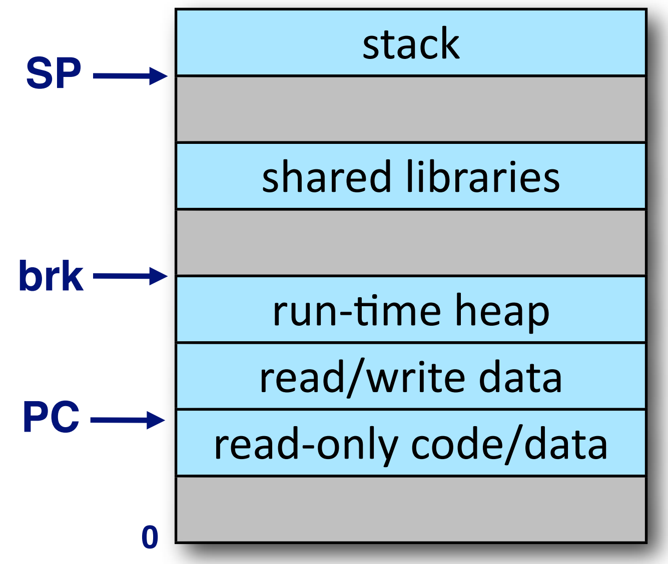
# Traditional View of a Process

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

**Process context**

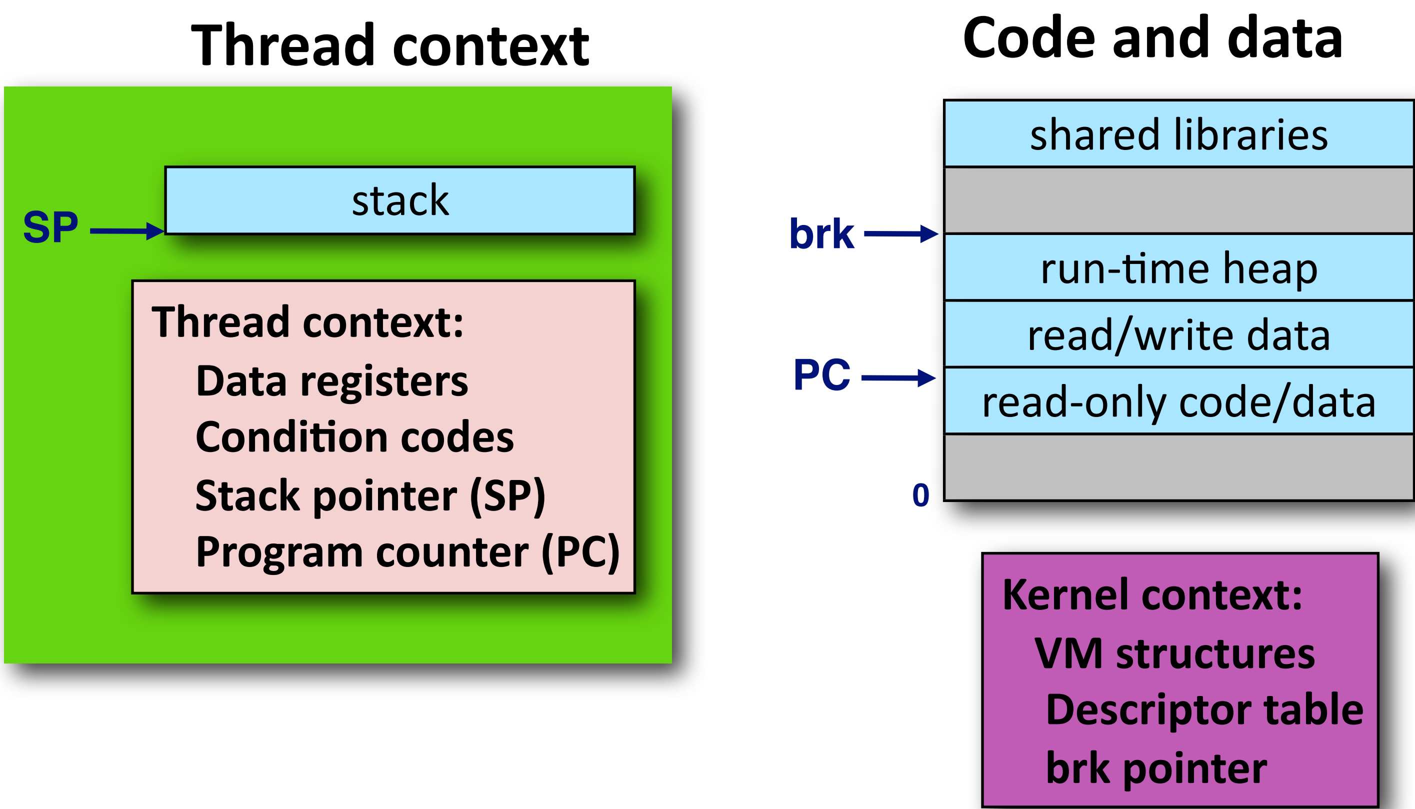
**Program context:**
Data registers
Condition codes
Stack pointer (SP)
Program counter (PC)
**Kernel context:**
VM structures
Descriptor table
brk pointer

**Code, data, and stack**



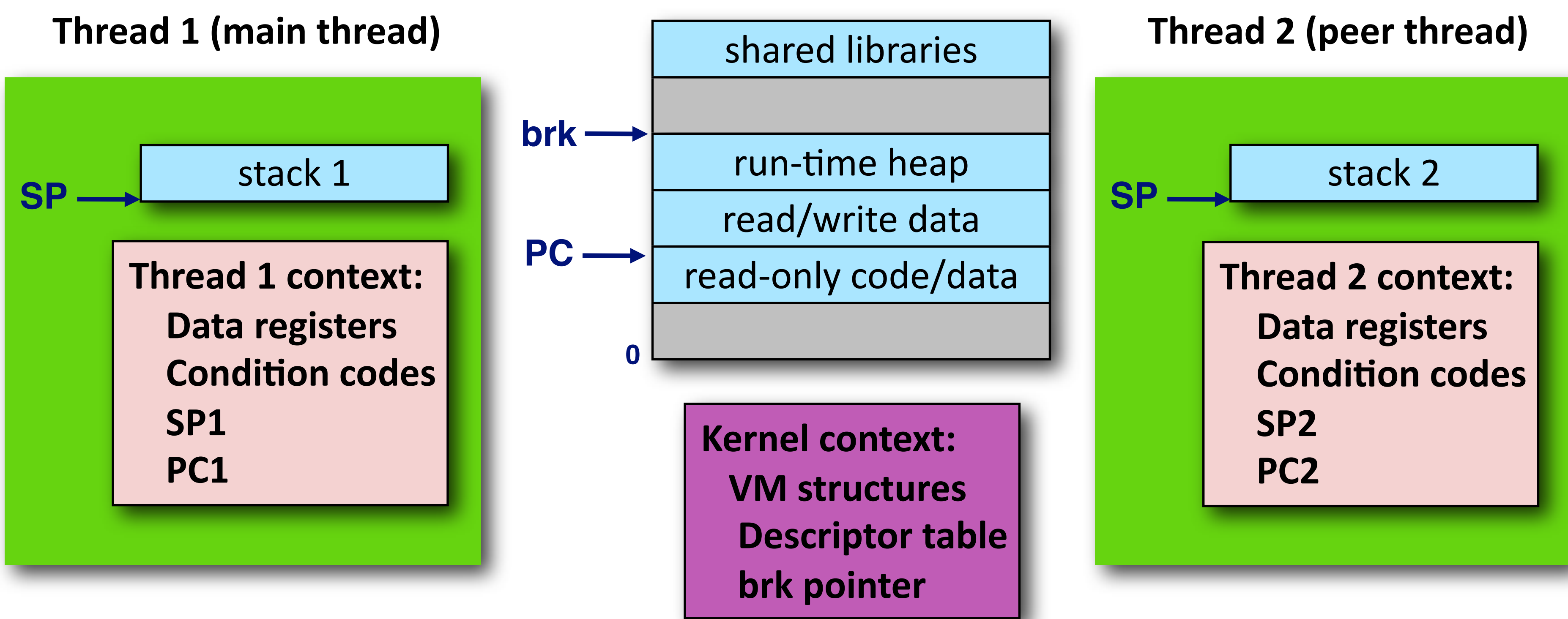
# Alternate View of a Process

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



# A Process With Multiple Threads

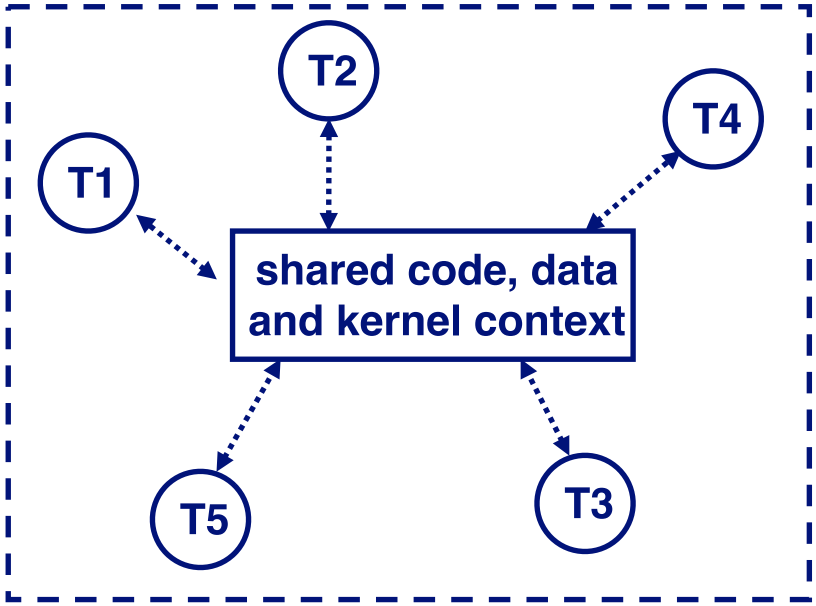
- **Multiple threads can be associated with a process**
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
    - Share common virtual address space
  - Each thread has its own thread id (TID)



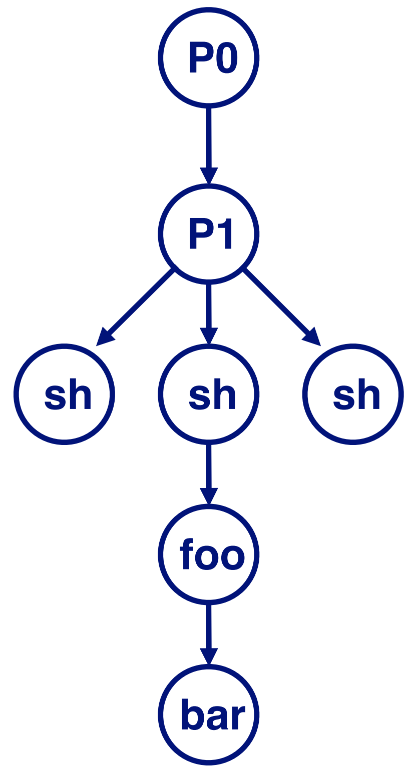
# Logical View of Threads

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

Threads associated with process foo




Process hierarchy



# 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 C interface with ~100 functions that manipulate threads**
  - 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

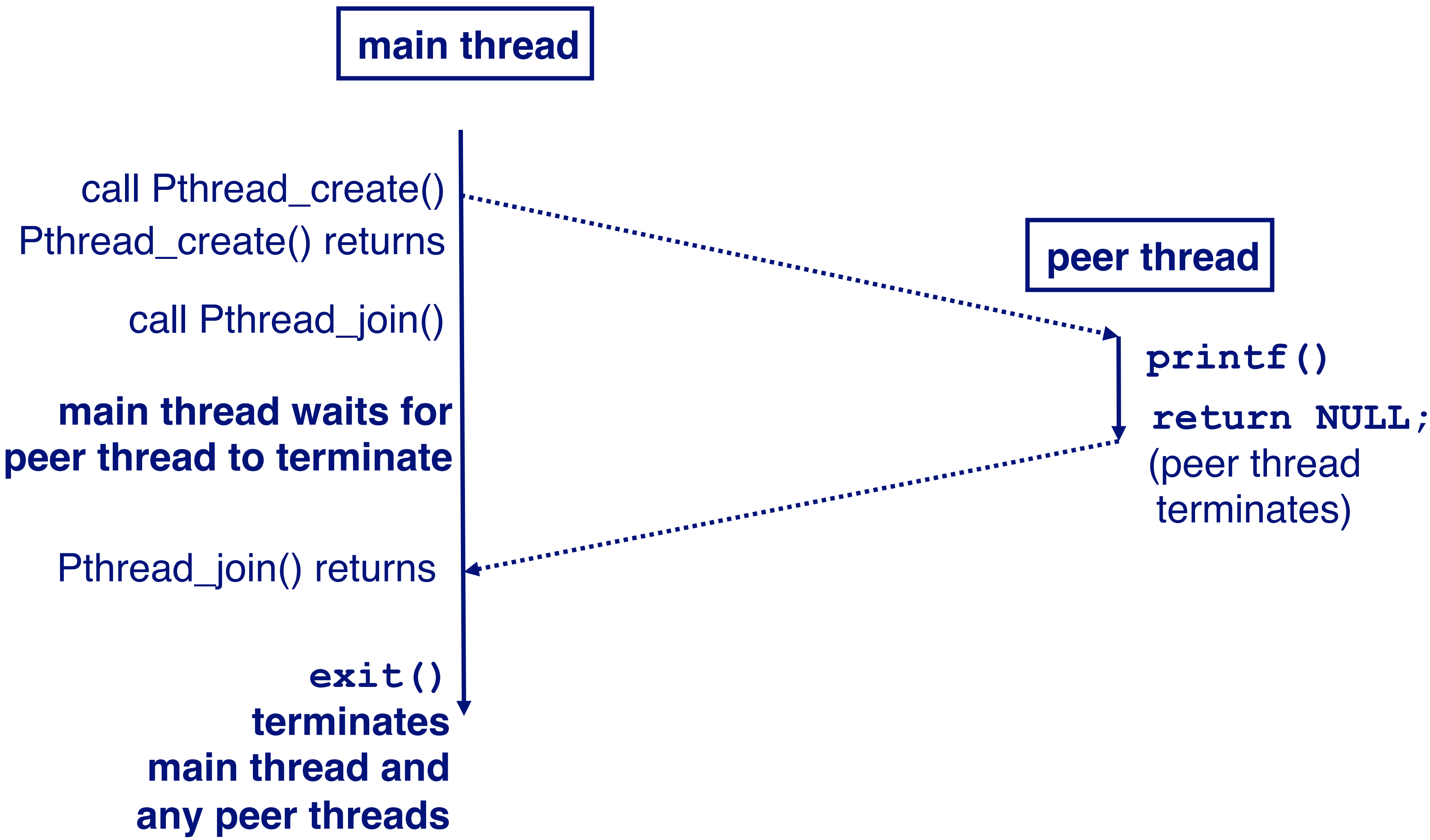
```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

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);
  }
}
```

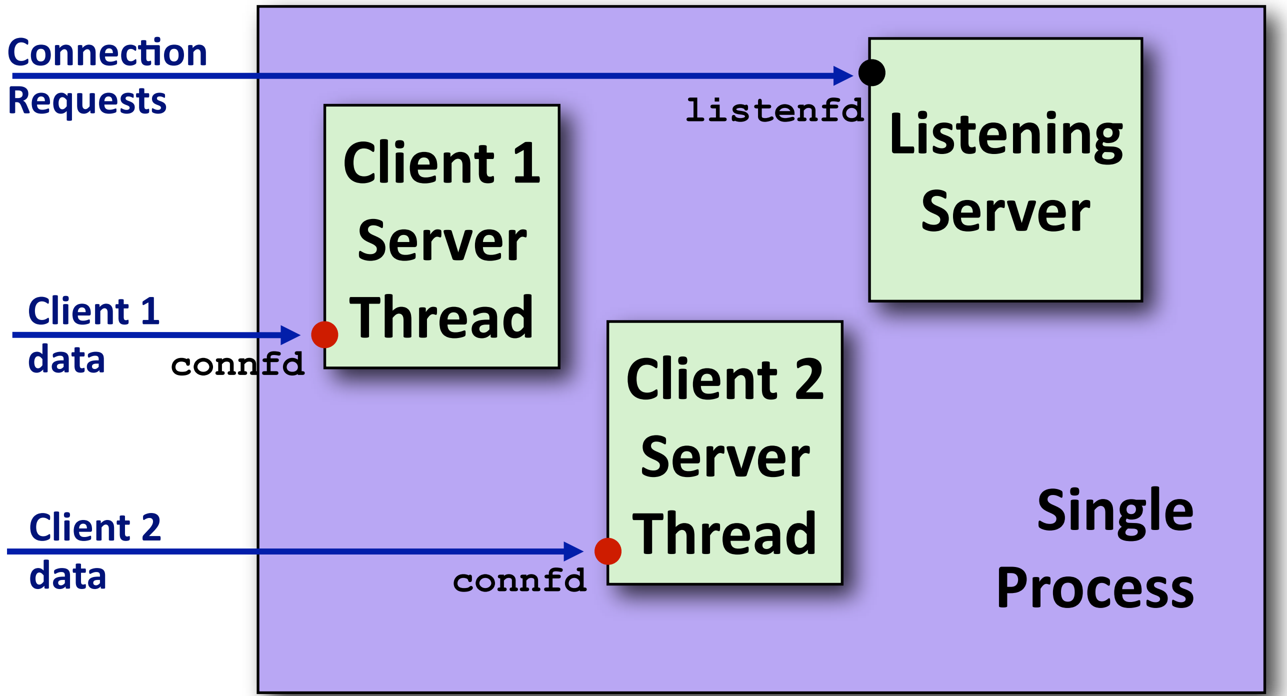
- **Spawn new thread for each client**
- **Pass it copy of connection file descriptor**
- **Note use of `Malloc()`**
  - Without corresponding `Free()`

# 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

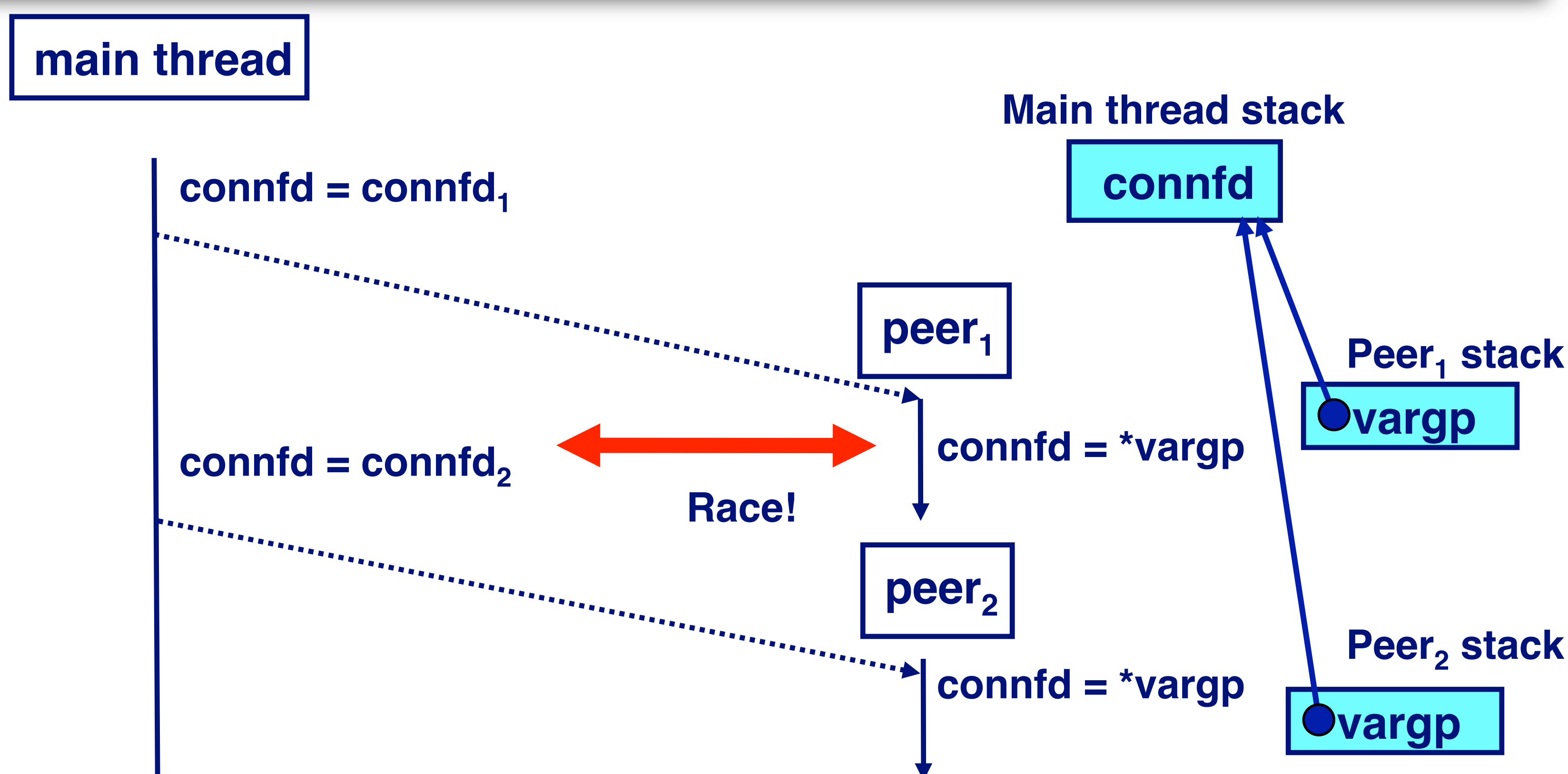
# Threaded-Process Execution Model




- **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);
  }
}
```




***Why would both copies of vargp point to same location?***

# 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)

# Today

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

# 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 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(fd_set *fdset);`**

- Turn on all bits in **`fdset`**

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

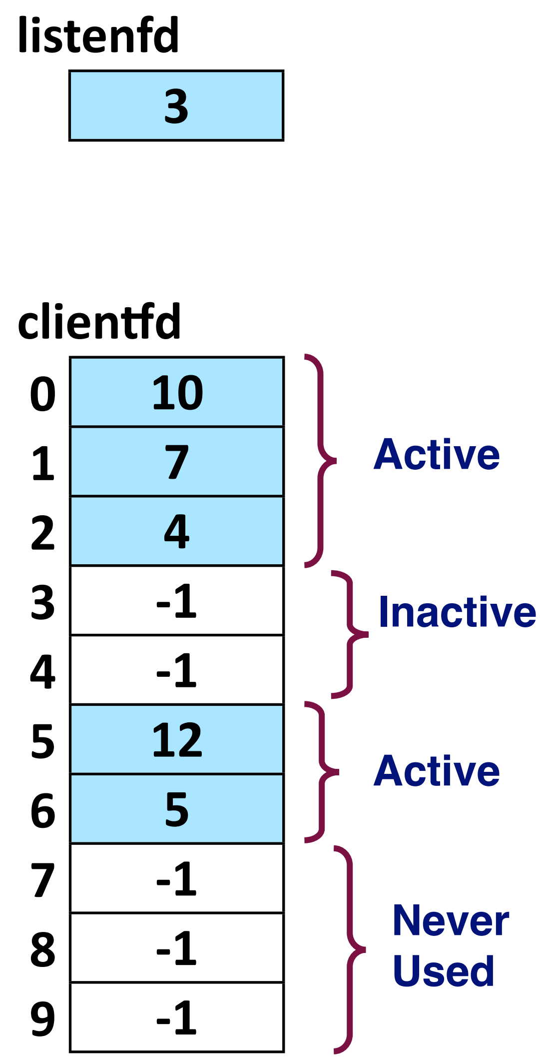
- Turn off bit **`fd`** in **`fdset`**

**`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
    - file descriptors kept in **`clientfd[ ]`**
- **Use `select()` to detect activity**
  - New request on **`listenfd`**
  - Request by active client
- **Required Activities**
  - Adding new clients
  - Removing terminated clients
  - Echoing



# Representing a 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

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

**listenfd**

| |
|---|
| 3 |

**clientfd**

| | |
|---|---|
| 0 | 10 |
| 1 | 7 |
| 2 | 4 |
| 3 | -1 |
| 4 | -1 |
| 5 | 12 |
| 6 | 5 |
| 7 | -1 |
| 8 | -1 |
| 9 | -1 |

# 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

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

listenfd

| |
|---|
| 3 |

clientfd

| | |
|---|---|
| 0 | -1 |
| 1 | -1 |
| 2 | -1 |
| 3 | -1 |
| 4 | -1 |
| 5 | -1 |
| 6 | -1 |
| 7 | -1 |
| 8 | -1 |
| 9 | -1 |

# 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

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

listenfd

| |
|---|
| 3 |

clientfd (before)

| | clientfd |
|---|---|
| 0 | 10 |
| 1 | 7 |
| 2 | 4 |
| 3 | -1 |
| 4 | -1 |
| 5 | 12 |
| 6 | 5 |
| 7 | -1 |
| 8 | -1 |
| 9 | -1 |

clientfd (after)

| | clientfd |
|---|---|
| 0 | 10 |
| 1 | 7 |
| 2 | 4 |
| 3 | 11 |
| 4 | -1 |
| 5 | 12 |
| 6 | 5 |
| 7 | -1 |
| 8 | -1 |
| 9 | -1 |

# Checking Clients

```
/* echo line from ready descs in pool p */
void check_clients(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

**- More complex code than process- or thread-based designs**

**- Hard to provide fine-grained concurrency**

- E.g., our example will hang up with partial lines

**- Does not make use of multiple cores**

# 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
  - Single thread – single core

# Today

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

- **Next Time:**
  - Synchronization