Concurrent Servers and Threads

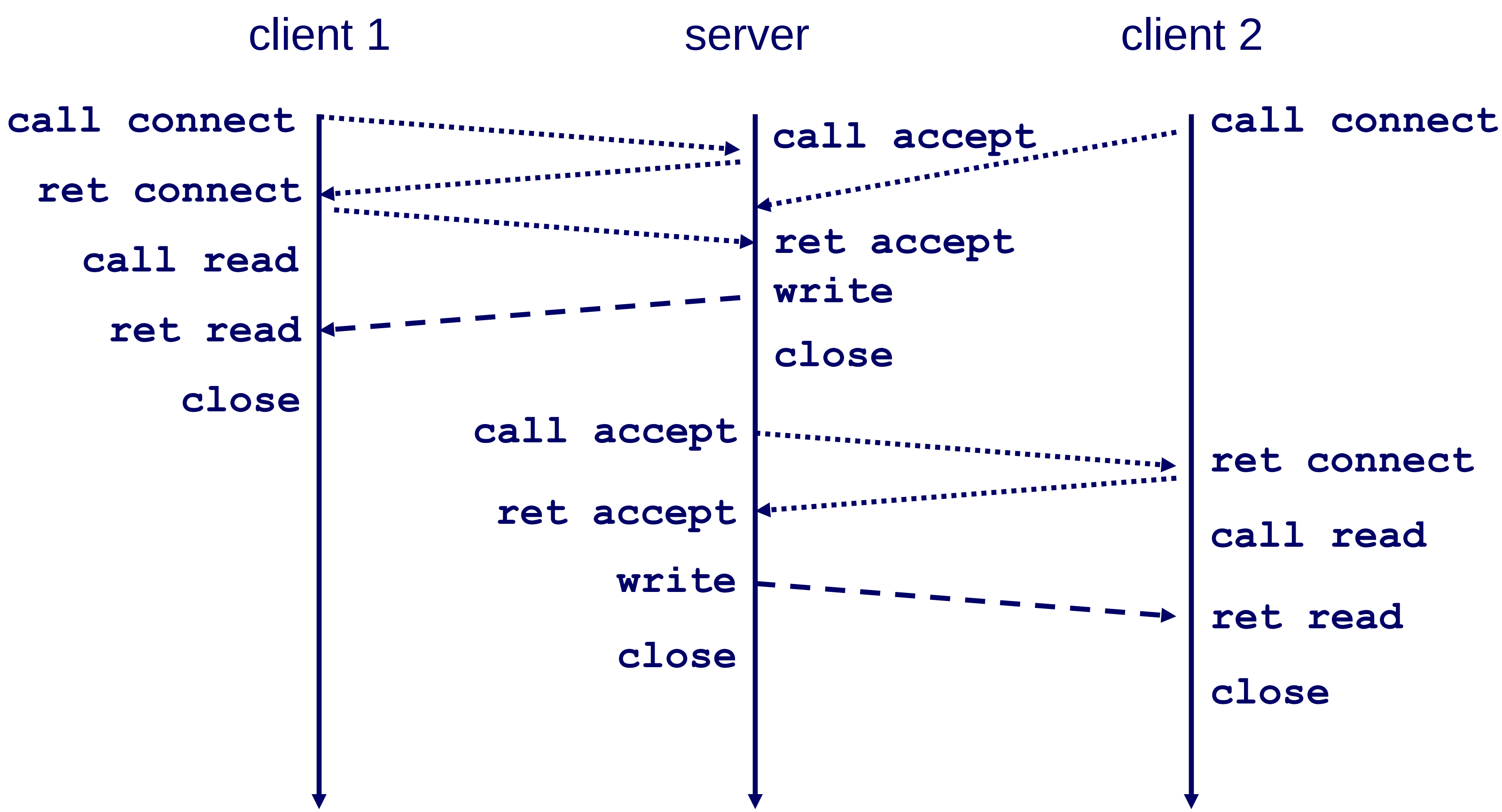
Ref: • "Computer Systems: A Programmer's Perspective", Bryant and O'Hallaron, First edition, Pearson Education, 2003

Topics

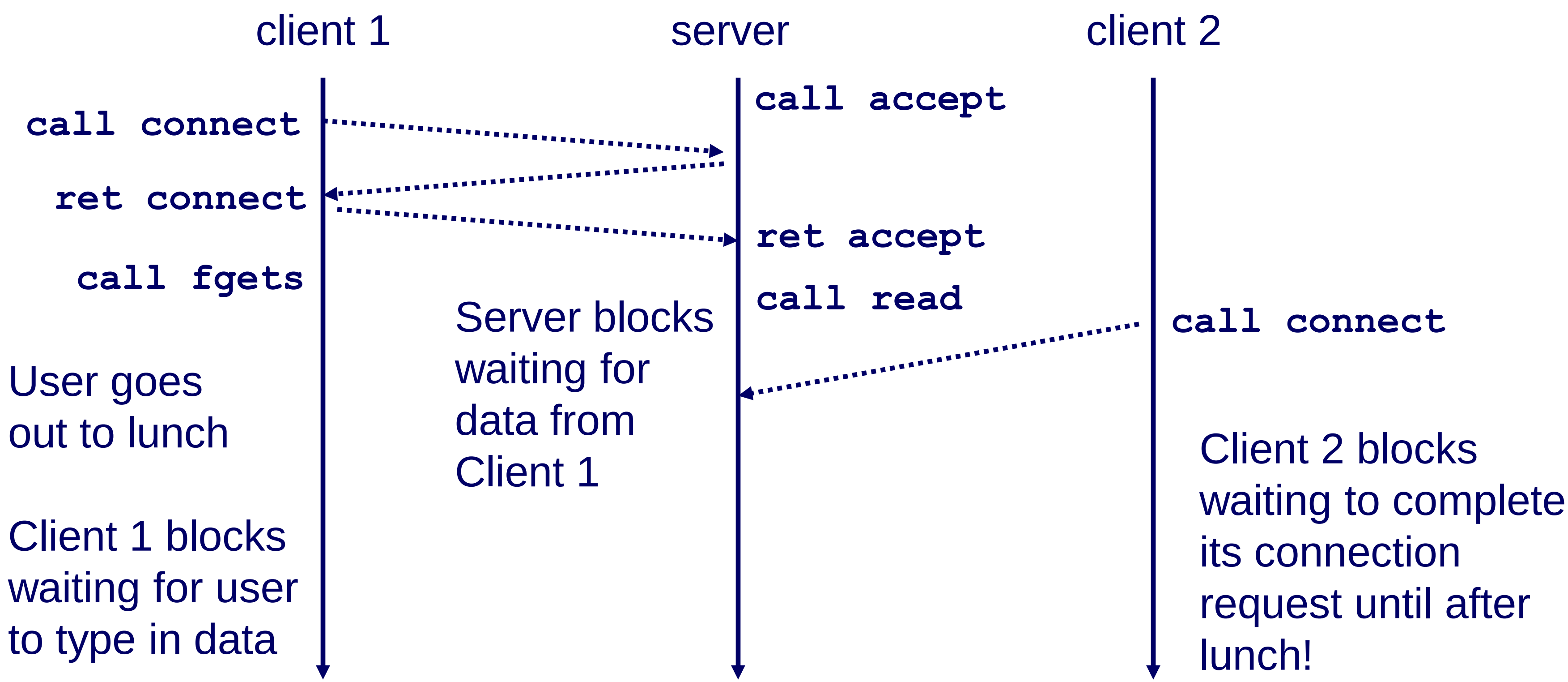
- Limitations of iterative servers
- Process-based concurrent servers
- Event-based concurrent servers
- Threads-based concurrent servers

Iterative Servers

Iterative servers process one request at a time.



Fundamental Flaw of Iterative Servers

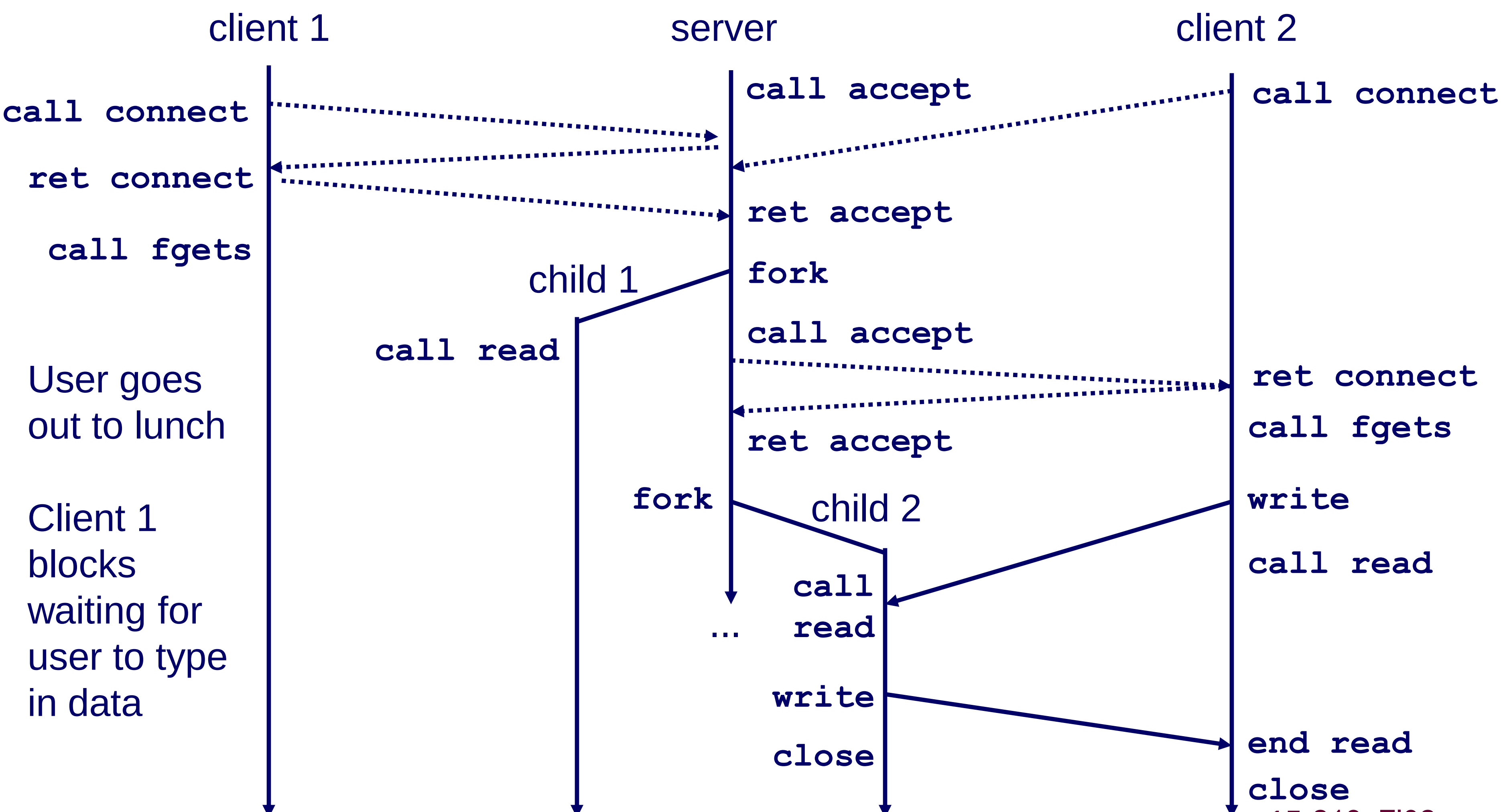


Solution: use *concurrent servers* instead.

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

Concurrent Servers

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. I/O multiplexing with `select()`

- User manually interleaves multiple logical flows.
- Each flow shares the same address space.
- Popular for high-performance server designs.

3. Threads

- Kernel automatically interleaves multiple logical flows.
- Each flow shares the same address space.
- Hybrid of processes and I/O multiplexing!

Process-Based Concurrent Server

```
/*
 * echoserverp.c - A concurrent echo server based on processes
 * Usage: echoserverp <port>
 */
#include <ics.h>
#define BUFSIZE 1024
void echo(int connfd);
void handler(int sig);

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

  if (argc != 2) {
    fprintf(stderr, "usage: %s <port>\n", argv[0]);
    exit(0);
  }
  portno = atoi(argv[1]);
  listenfd = open_listenfd(portno);
```

Process-Based Concurrent Server (cont)

```
 Signal(SIGCHLD, handler); /* parent must reap children! */

  /* main server loop */
  while (1) {
    connfd = Accept(listenfd, (struct sockaddr *) &clientaddr,
                            &clientlen));
    if (Fork() == 0) {
      Close(listenfd); /* child closes its listening socket */
      echo(connfd);    /* child reads and echoes input line */
      Close(connfd);   /* child is done with this client */
      exit(0);         /* child exits */
    }
    Close(connfd); /* parent must close connected socket! */
  }
}
```

Process-Based Concurrent Server (cont)

```
/* handler - reaps children as they terminate */
void handler(int sig) {
  pid_t pid;
  int stat;

  while ((pid = waitpid(-1, &stat, WNOHANG)) > 0)
    ;
  return;
}
```

Implementation Issues With Process-Based Designs

Server should restart `accept` call if it is interrupted by a transfer of control to the SIGCHLD handler

- Not necessary for systems with POSIX signal handling.
  - Our `Signal` wrapper tells kernel to automatically restart `accept`
- Required for portability on some older Unix systems.

Server must reap zombie children

- to avoid fatal memory leak.

Server must `close` its copy of `connfd`.

- Kernel keeps reference for each socket.
- 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

I/O multiplexing provides more control with less overhead...

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` are 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?

select Example

```
/*
 * main loop: wait for connection request or stdin command.
 * If connection request, then echo input line
 * and close connection. If stdin command, then process.
 */
printf("server> ");
fflush(stdout);

while (notdone) {
    /*
     * select: check if the user typed something to stdin or
     * if a connection request arrived.
     */
    FD_ZERO(&readfds);          /* initialize the fd set */
    FD_SET(listenfd, &readfds); /* add socket fd */
    FD_SET(0, &readfds);        /* add stdin fd (0) */
    Select(listenfd+1, &readfds, NULL, NULL, NULL);
```

`select` Example (cont)

First we check for a pending event on stdin.

```
/* if the user has typed a command, process it */
if (FD_ISSET(0, &readfds)) {
   fgets(buf, BUFSIZE, stdin);
   switch (buf[0]) {
   case 'c': /* print the connection count */
      printf("Received %d conn. requests so far.\n", connectcnt);
      printf("server> ");
      fflush(stdout);
      break;
   case 'q': /* terminate the server */
      notdone = 0;
      break;
   default: /* bad input */
      printf("ERROR: unknown command\n");
      printf("server> ");
      fflush(stdout);
   }
}
```

select Example (cont)

Next we check for a pending connection request.

```
   /* if a connection request has arrived, process it */
   if (FD_ISSET(listenfd, &readfds)) {
      connfd = Accept(listenfd,
                      (struct sockaddr *) &clientaddr, &clientlen);
      connectcnt++;

      bzero(buf, BUFSIZE);
      Rio_readn(connfd, buf, BUFSIZE);
      Rio_writen(connfd, buf, strlen(buf));
      Close(connfd);
   }
} /* while */
```

Event-based Concurrent Echo Server

```
/*
 * 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 */
```

Event-based Concurrent Server (cont)

```
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);
    }
}
```

Event-based Concurrent Server (cont)

```
/* 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);
}
```

Event-based Concurrent Server (cont)

```
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");
}
```

Event-based Concurrent Server (cont)

```
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;
            }
        }
    }
}
```

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.

- Can be vulnerable to denial of service attack

  - How?

Threads provide a middle ground between processes and I/O multiplexing...

Traditional View of a Process

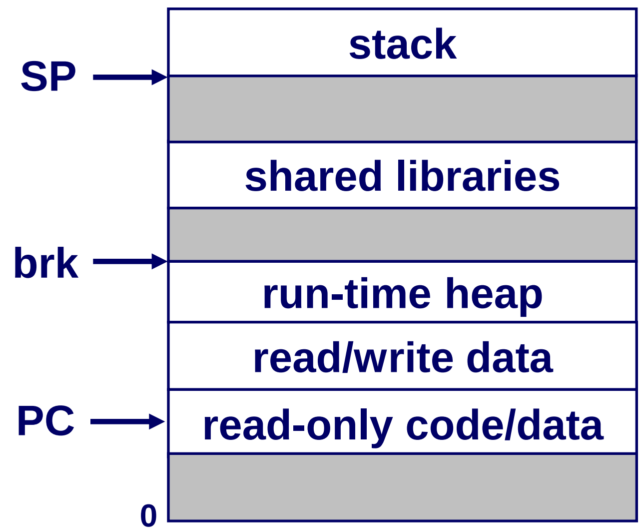
Process = process context + code, data, and stack

Process context

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

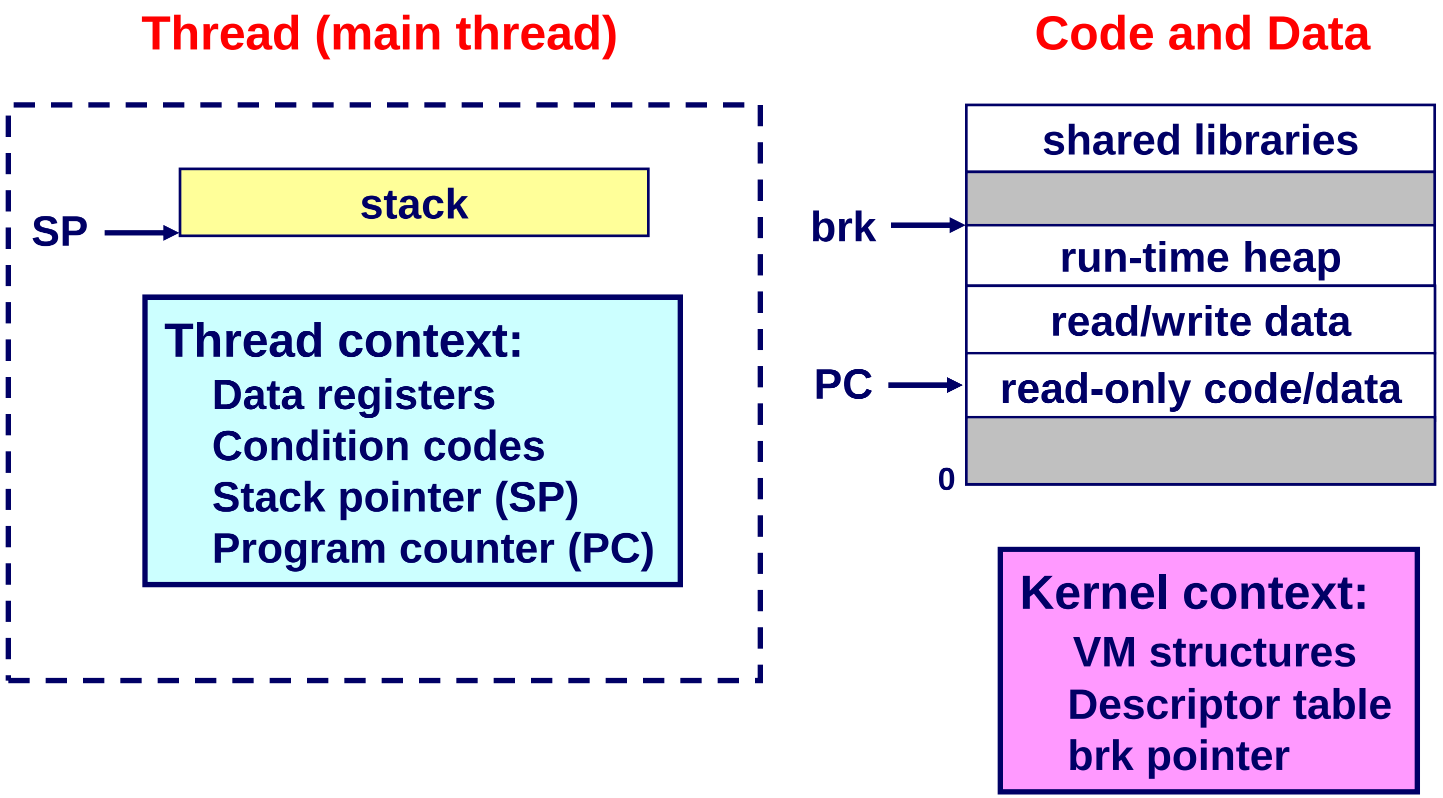
Kernel context:
- VM structures
- Descriptor table
- brk pointer

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 (sequence of PC values)
- Each thread shares the same code, data, and kernel context
- Each thread has its own thread id (TID)

Thread 1 (main thread)

stack 1

Thread 1 context:
Data registers
Condition codes
SP1
PC1

Shared code and data

shared libraries
run-time heap
read/write data
read-only code/data

0

Kernel context:
VM structures
Descriptor table
brk pointer

Thread 2 (peer thread)

stack 2

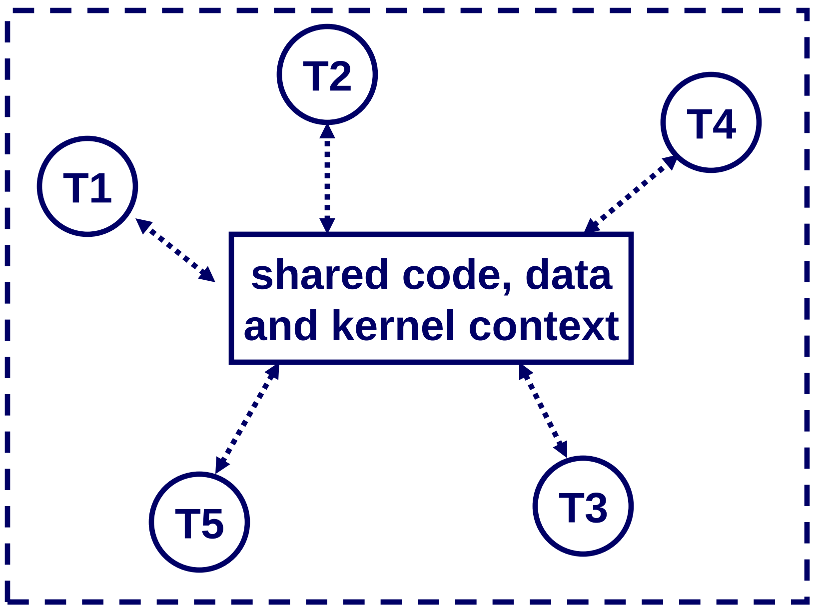
Thread 2 context:
Data registers
Condition codes
SP2
PC2

Logical View of Threads

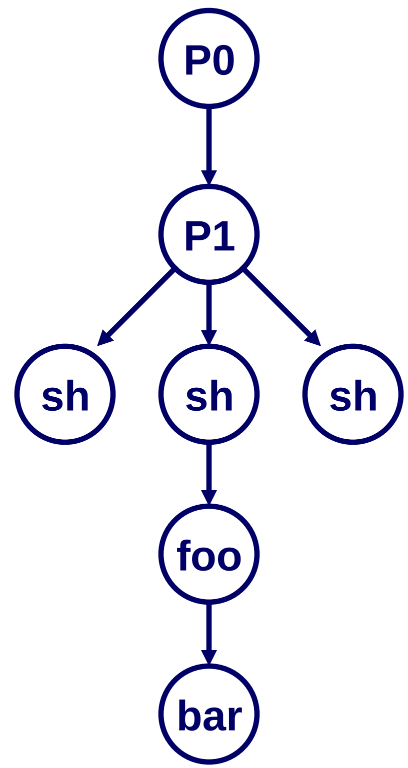
Threads associated with a process form a pool of peers.

- Unlike processes which form a tree hierarchy

Threads associated with process foo



Process hierarchy



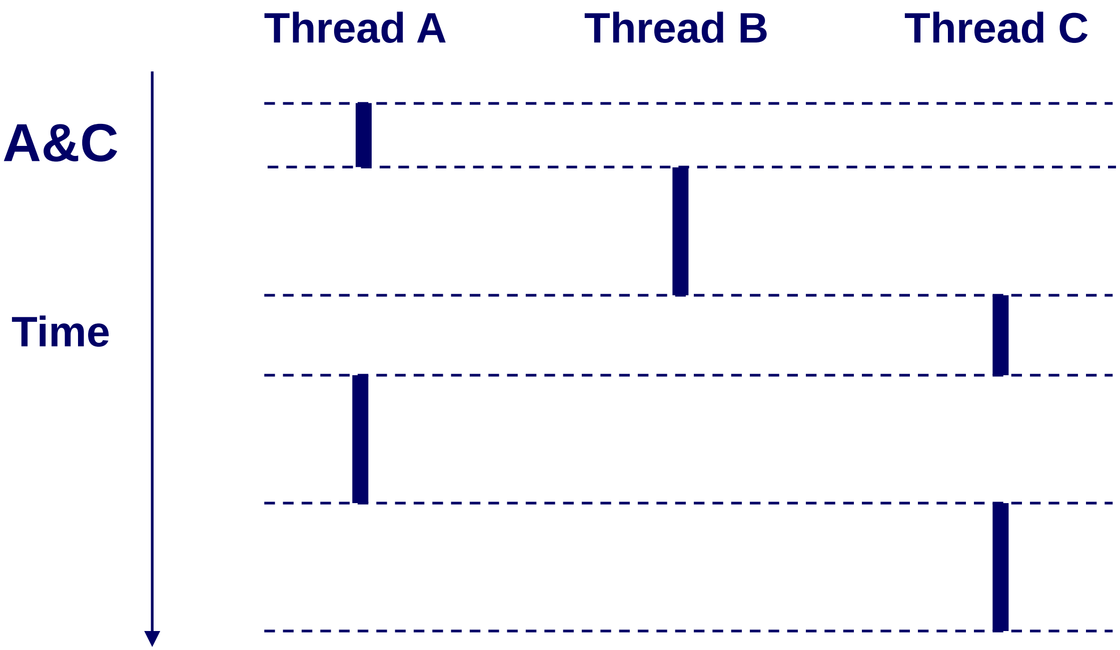
Concurrent Thread Execution

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

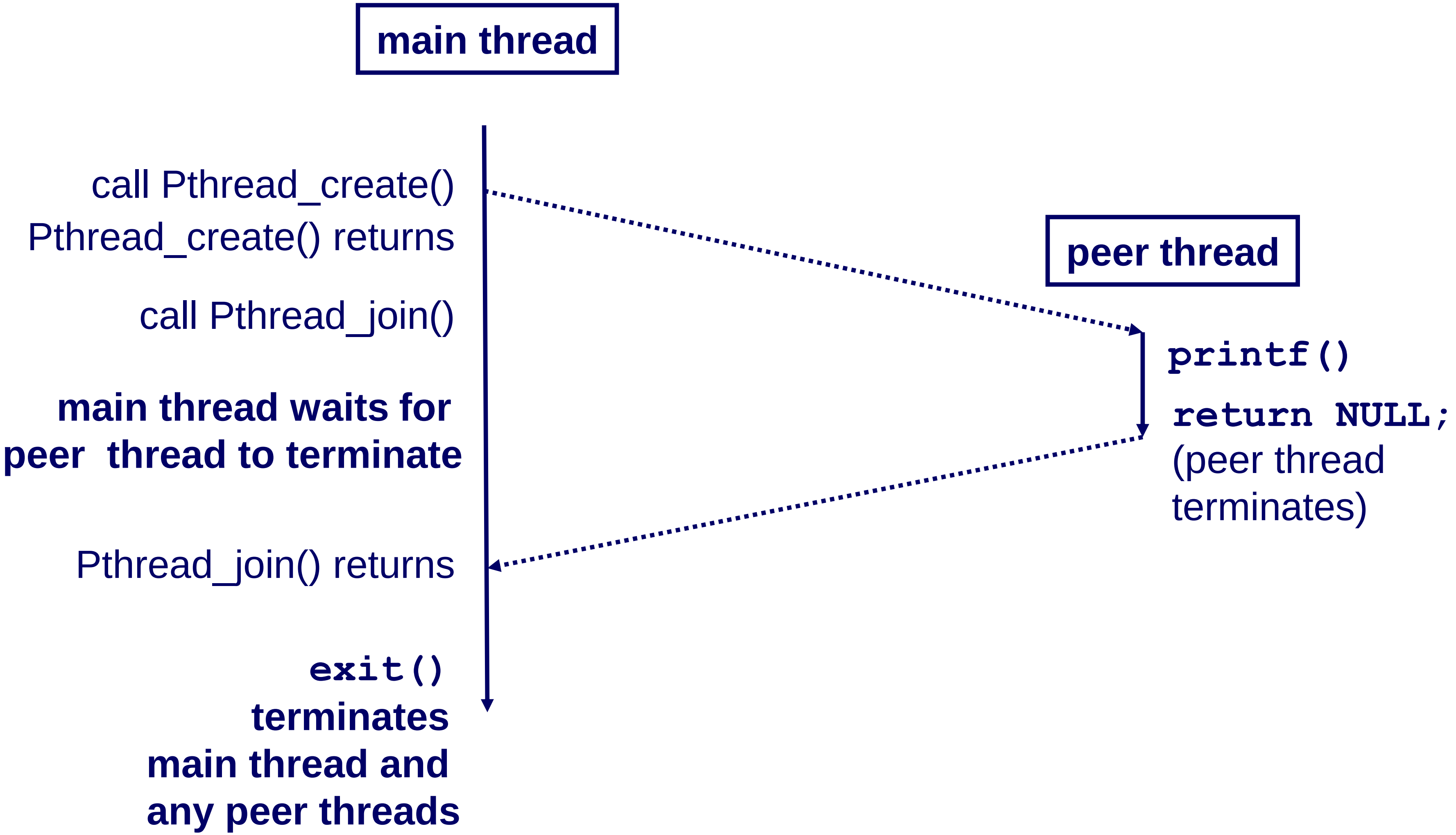
```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

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”



Creation of a thread

pthread_create function creates a new thread and runs the thread routine in the context of new thread with argument of arg.

Attr argument can be used to change the default attributes of the newly created thread, can be NULL

When pthread_create returns, argument tid contains ID of the newly created thread.

New thread can determine its own thread ID by calling pthread_self function.

- pthread_t pthread_self(void);

Termination of threads

Terminates implicitly when its top-level thread routine returns.

Terminates explicitly by calling pthread_exit function, which returns a pointer to the return value thread_return.

If main thread call pthread_exit, it waits for all other peer threads to terminate, and then terminates the main thread and the entire process with a return value of thread_return.

- int pthread_exit(void *thread_return);

Some peer thread calls the Unix exit funcion, which terminates the process and all thread associated with the process.

Another peer thread terminates the current thread by calling the pthread_cancel function with the ID of the current thread.

- int pthread_cancel(pthread_t tid);

Reaping terminated threads

Threads waits for other threads to terminate by calling the pthread_join function

Int pthread_join(pthread_t tid, void **thread_return);

It blocks until tread tid terminates, assigns the (void *) pointer returned by the thread routine to the location pointed to by thread_return, and then reaps any memory resources held by the terminates thread.

Unlike unix wait function, pthread_join function can only wait for a specific thread to terminate. There is no way to instruct pthread_wait to wait for an arbitrary thread to terminate.

Detaching threads

- At any point in time, a thread is joinable or detached.
- Joinable thread: can be reaped and killed by other threads. Its memory resources (e.g. stack) are not freed until it is reaped by another thread. By default.
- Detached thread: can not be reaped or killed by other thread. Its memory resources are freed automatically by the system when it terminates.
- Each joinable thread should either be explicitly reaped by another thread, or detached by a call to the pthread_detach function.

  ```
  int pthread_detach(pthread_t tid);
  ```

- A thread can detach itself by calling pthread_detach with an argument of pthread_self().
- Better to use detached threads: performance, connections

Initializing Threads

```
Pthread_once_t once_control = PTHREAD_ONCE_INIT;

int pthread_once(pthread_once_t *once_control, void
   (*init_routine) (void));
```

To initialize the state associated with a thread routine.

once_control is a global or static variable that is always initialized to PTHREAD_ONCE_INIT. When you call for the first time with an argument of once_control, it invokes init_routine, which is a function with no arguments that returns nothing.

Subsequent call to pthread_once with an argument of thread_once do nothing.

This function is useful whenever you need to dynamically initialize global variables that are shared by multiple thread.

Thread-Based Concurrent Echo Server

```
#include "csapp.h"
Void echo (int connfd); void *thread(void *vargp);
int main(int argc, char **argv)
{
    int listenfd, *connfdp, port, clientlen;
    struct sockaddr_in clientaddr;
    pthread_t tid;

    if (argc != 2) {
        fprintf(stderr, "usage: %s <port>\n", argv[0]);
        exit(0);
    }
    port = atoi(argv[1]);

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

Thread-Based Concurrent Server (cont)

```
* thread routine */
void *thread(void *vargp)
{
    int connfd = *((int *)vargp);

    Pthread_detach(pthread_self());
    Free(vargp);

    echo_r(connfd); /* reentrant version of echo() */
    Close(connfd);
    return NULL;
}
```

Thread-Based Concurrent Server (cont)

Issues:

How to pass the connected descriptor to the peer thread when we call pthread_create?

To pass a pointer to the descriptor, e.g.

```
connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);

Pthread_create(&tid, NULL, thread, &connfd);
```

Peer thread dereferences the pointer and assign it to a local variable, e.g.

```
void *thread(void *vargp)

{    int connfd = *((int *)vargp); …}
```

Thread-Based Concurrent Server (cont)

It would be wrong, as it introduces a *race* between the assignment statement in the peer thread and the accept statement in the main thread.

If assignment statement completes before the next accept, the the local connfd variable in the peer thread gets the correct descriptor value.

If assignment statement completes after the next accept, the the local connfd variable in the peer thread gets the descriptor value of next connection.

- Now two threads are performing input and output on the same descriptor

Thread-Based Concurrent Server (cont)

In order to avoid the potentially deadly race, we must assign each connected descriptor returned by its own dynamically allocated memory block

```
clientlen = sizeof(clientaddr);

connfdp = Malloc(sizeof(int));

*connfdp = Accept(listenfd, (SA *) &clientaddr,
   &clientlen);

Pthread_create(&tid, NULL, thread, connfdp);
```

Thread-Based Concurrent Server (cont)

Another issue is to avoid memory leaks in the thread routine.

Since we are not explicitly reaping threads, we must detach each thread so that its memory resources will be reclaimed when it terminates e.g.

```
Pthread_detach(pthread_self());
```

We must be careful to free the memory block that was allocated by the main thread, e.g.

```
Free(vargp);
```

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*

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.