Concurrent Programming

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Echo Server Revisited

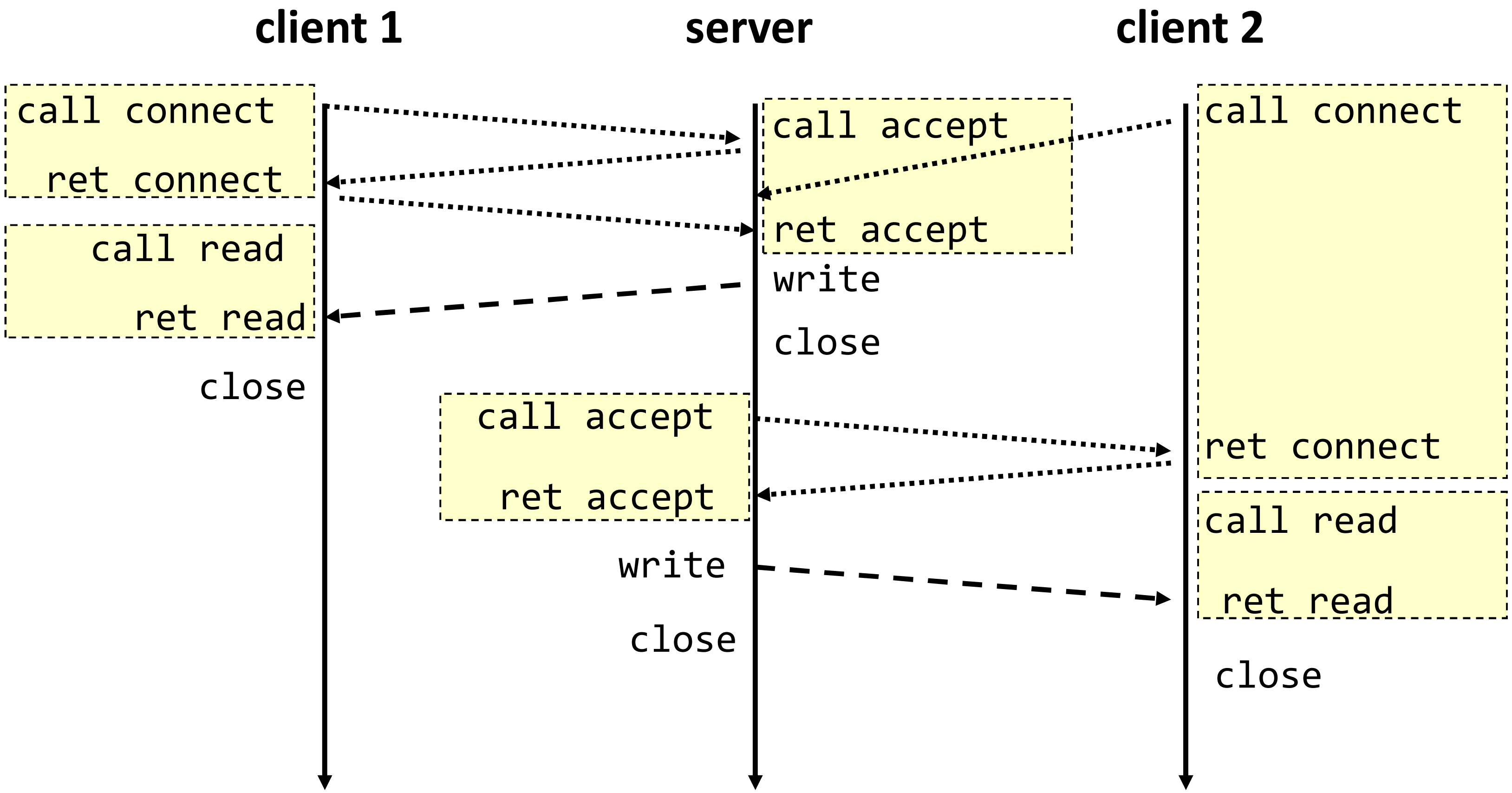
```
int main (int argc, char *argv[]) {
   ...
   listenfd = socket(AF_INET, SOCK_STREAM, 0);

   bzero((char *)&saddr, sizeof(saddr));
   saddr.sin_family = AF_INET;
   saddr.sin_addr.s_addr = htonl(INADDR_ANY);
   saddr.sin_port = htons(port);
   bind(listenfd, (struct sockaddr *)&saddr, sizeof(saddr));

   listen(listenfd, 5);
   while (1) {
      connfd = accept(listenfd, (struct sockaddr *)&caddr, &clen);
      while ((n = read(connfd, buf, MAXLINE)) > 0) {
         printf ("got %d bytes from client.\n", n);
         write(connfd, buf, n);
      }
      close(connfd);
   }
}
```

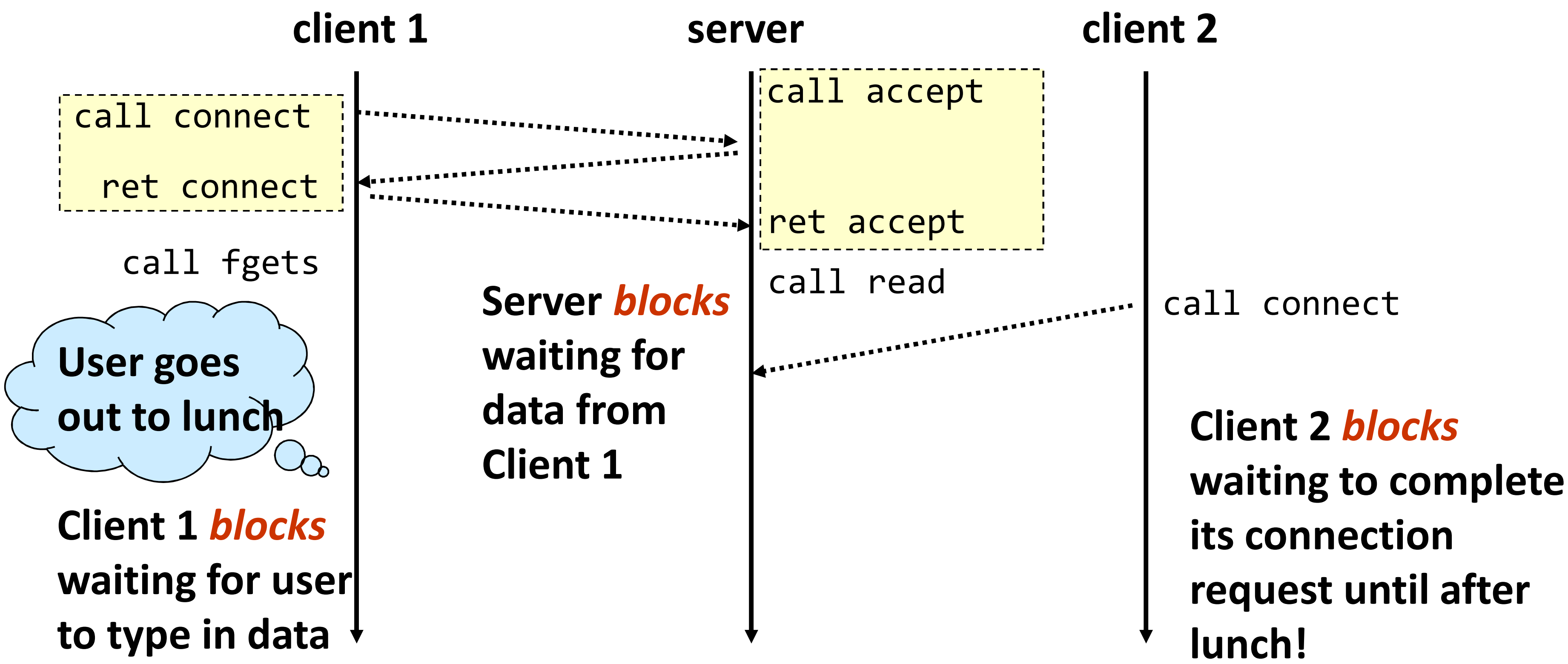
Iterative Servers (1)

- One request at a time



Iterative Servers (2)

- **Fundamental flaw**



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

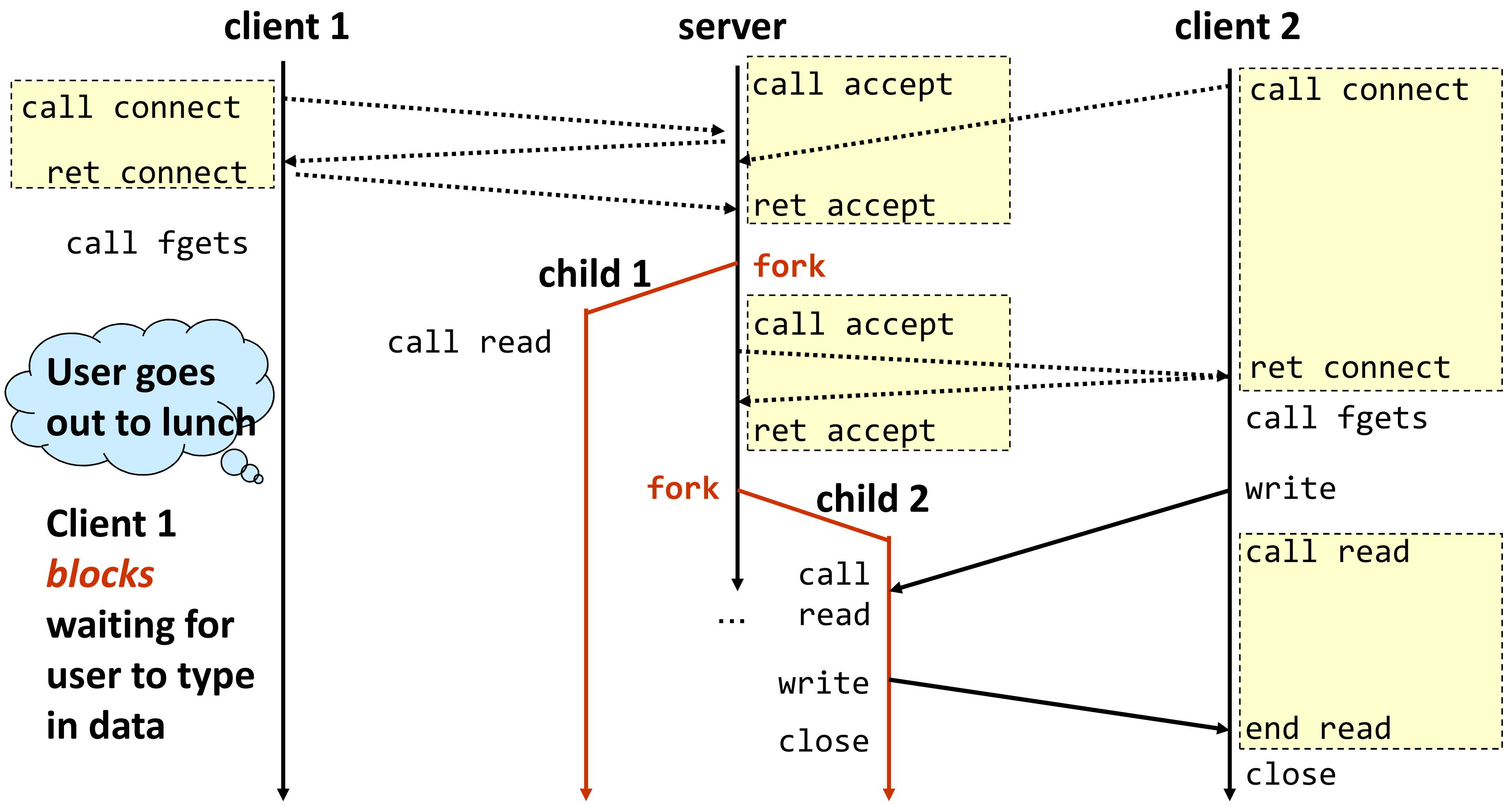
Creating Concurrent Flows

- **Processes**
  - Kernel automatically interleaves multiple logical flows.
  - Each flow has its own private address space.
- **Threads**
  - Kernel automatically interleaves multiple logical flows.
  - Each flow shares the same address space.
  - Hybrid of processes and I/O multiplexing
- **I/O multiplexing with select()**
  - User manually interleaves multiple logical flows
  - Each flow shares the same address space
  - Popular for high-performance server designs.

Concurrent Programming

Process-based

Process-based Servers



Echo Server

- **Iterative version**

```
int main (int argc, char *argv[])
{
   . . .

   while (1) {
      connfd = accept (listenfd, (struct sockaddr *)&caddr,
                       &caddrlen));

      while ((n = read(connfd, buf, MAXLINE)) > 0) {
         printf (“got %d bytes from client.\n”, n);
         write(connfd, buf, n);
      }

      close(connfd);
   }
}
```

Echo Server: Process-based

```
int main (int argc, char *argv[])
{
   . . .
   signal (SIGCHLD, handler);

   while (1) {
      connfd = accept (listenfd, (struct sockaddr *)&caddr,
                       &caddrlen));
      if (fork() == 0) {
         close(listenfd);
         while ((n = read(connfd, buf, MAXLINE)) > 0) {
            printf ("got %d bytes from client.\n", n);
            write(connfd, buf, n);
         }
         close(connfd);
         exit(0);
      }
      close(connfd);
   }
}
```

```
void handler(int sig) {
   pid_t pid;
   int stat;
   while ((pid = waitpid(-1, &stat,
                         WNOHANG)) > 0);
   return;
}
```

Implementation Issues

- **Servers should restart accept() if it is interrupted by a transfer of control to the SIGCHLD handler**
  - Not necessary for systems with POSIX signal handling.
  - 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**

Process-based Designs

- **Pros**
  - Handles multiple connections concurrently.
  - Clean sharing model.
    - Descriptors (no), file tables (yes), global variables (no)
  - Simple and straightforward.
- **Cons**
  - Additional overhead for process control.
    - Process creation and termination
    - Process switching
  - Nontrivial to share data between processes.
    - Requires IPC (InterProcess Communication) mechanisms: FIFO's, System V shared memory and semaphores

Concurrent Programming

Thread-based

Traditional View

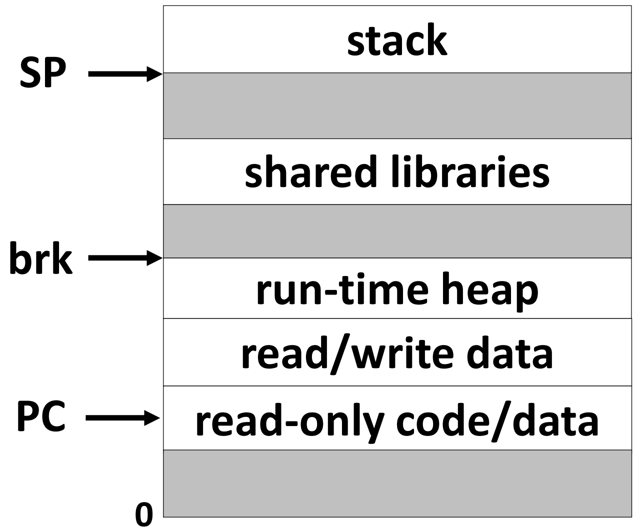
- **Process = process context + address space**

Process context

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

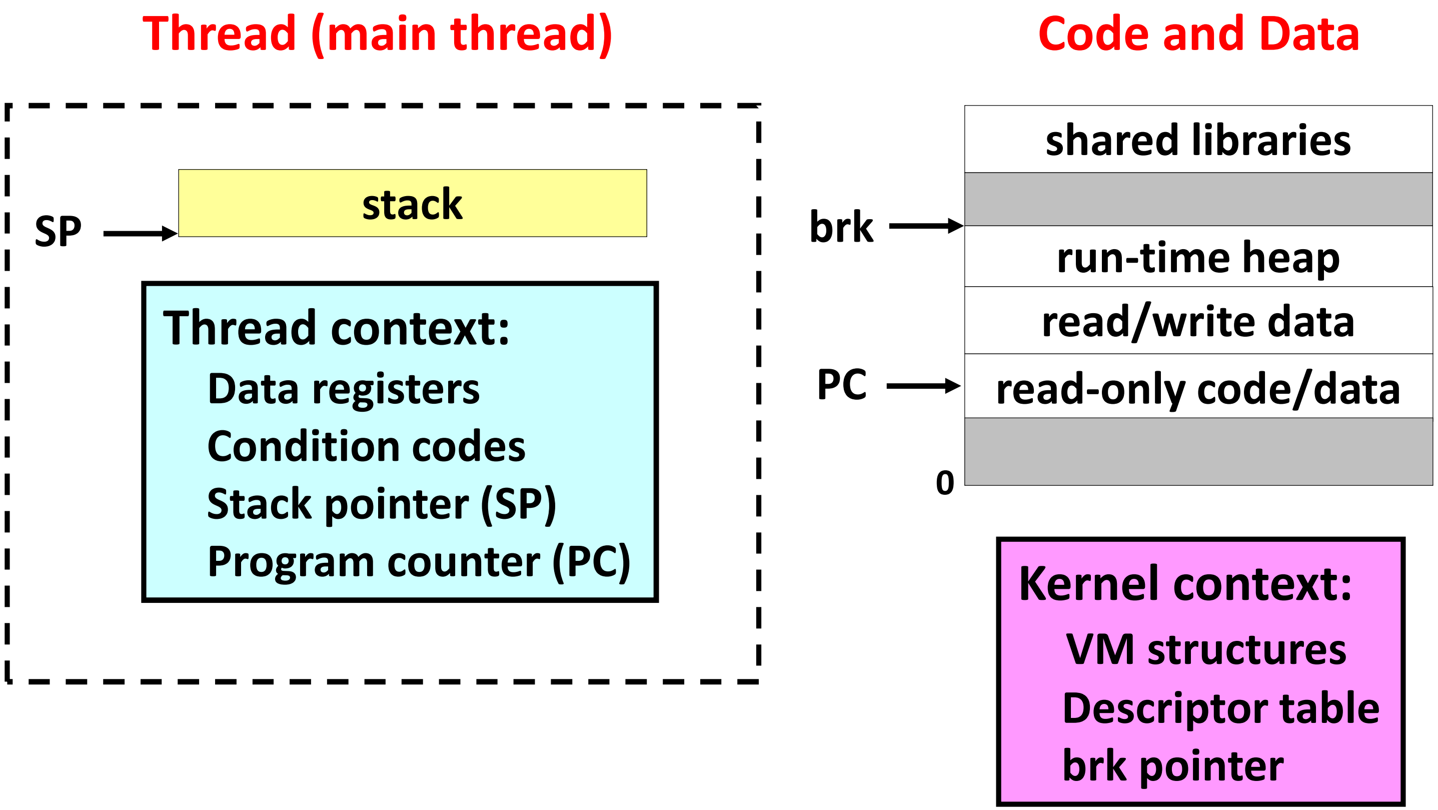
Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack



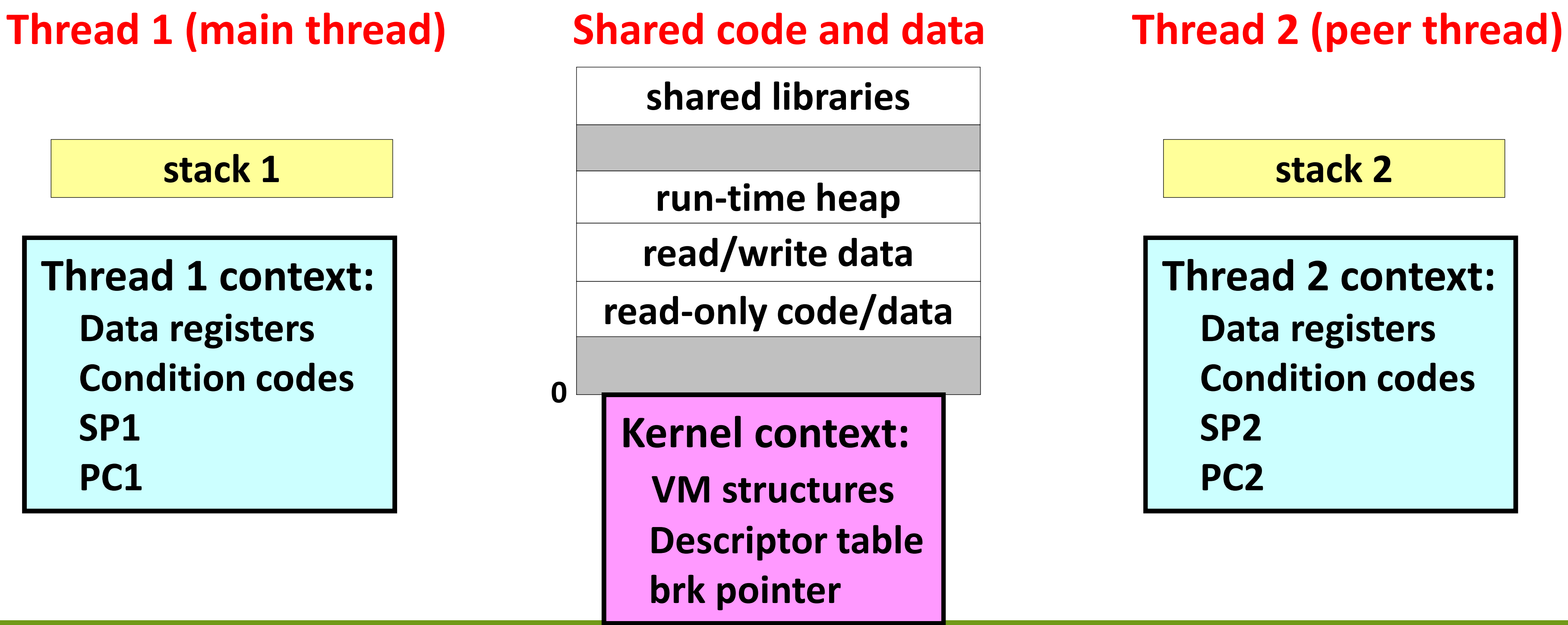
Alternate View

- Process = thread context + kernel context + address space



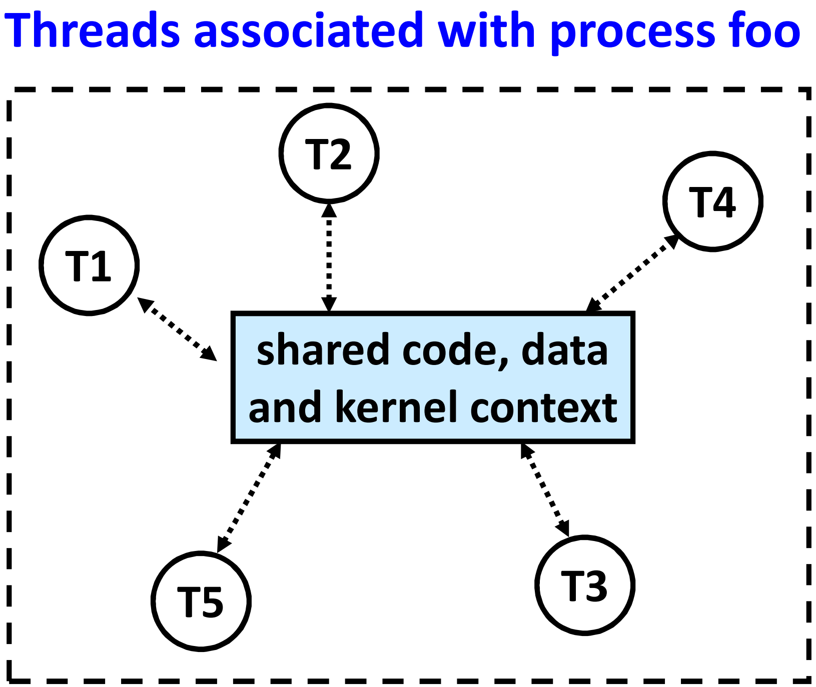
A Process with Multiple Threads

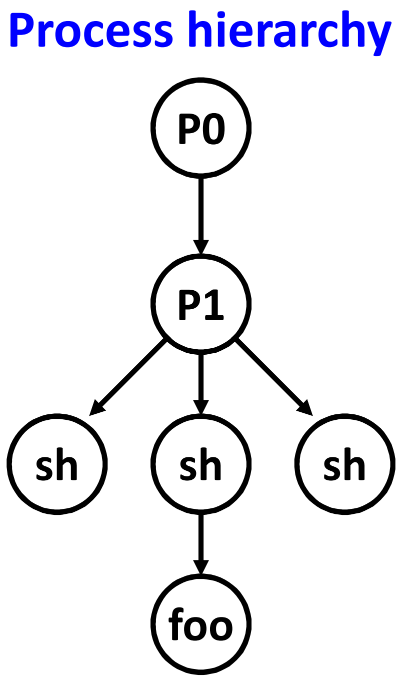
- **Multiple threads can be associated with a process.**
  - Each thread has its own logical control flow (sequence of PC values)
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own thread id (TID)



Logical View of Threads

- **Threads associated with a process form a pool of peers**
  - Unlike processes which form a tree 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.
    - Linux 2.4 Kernel, 512MB RAM, 2 CPUs

      -> 1,811 forks()/second

      -> 227,611 threads/second (125x faster)

Pthreads Interface

- **POSIX Threads Interface**
  - 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()**
    - **pthread_cond_init()**
    - **pthread_cond_[timed]wait()**
    - **pthread_cond_signal()**, etc.

“hello, world” Program (1)

```c
/*
 * hello.c - Pthreads "hello, world" program
 */
#include “pthread.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;
}
```

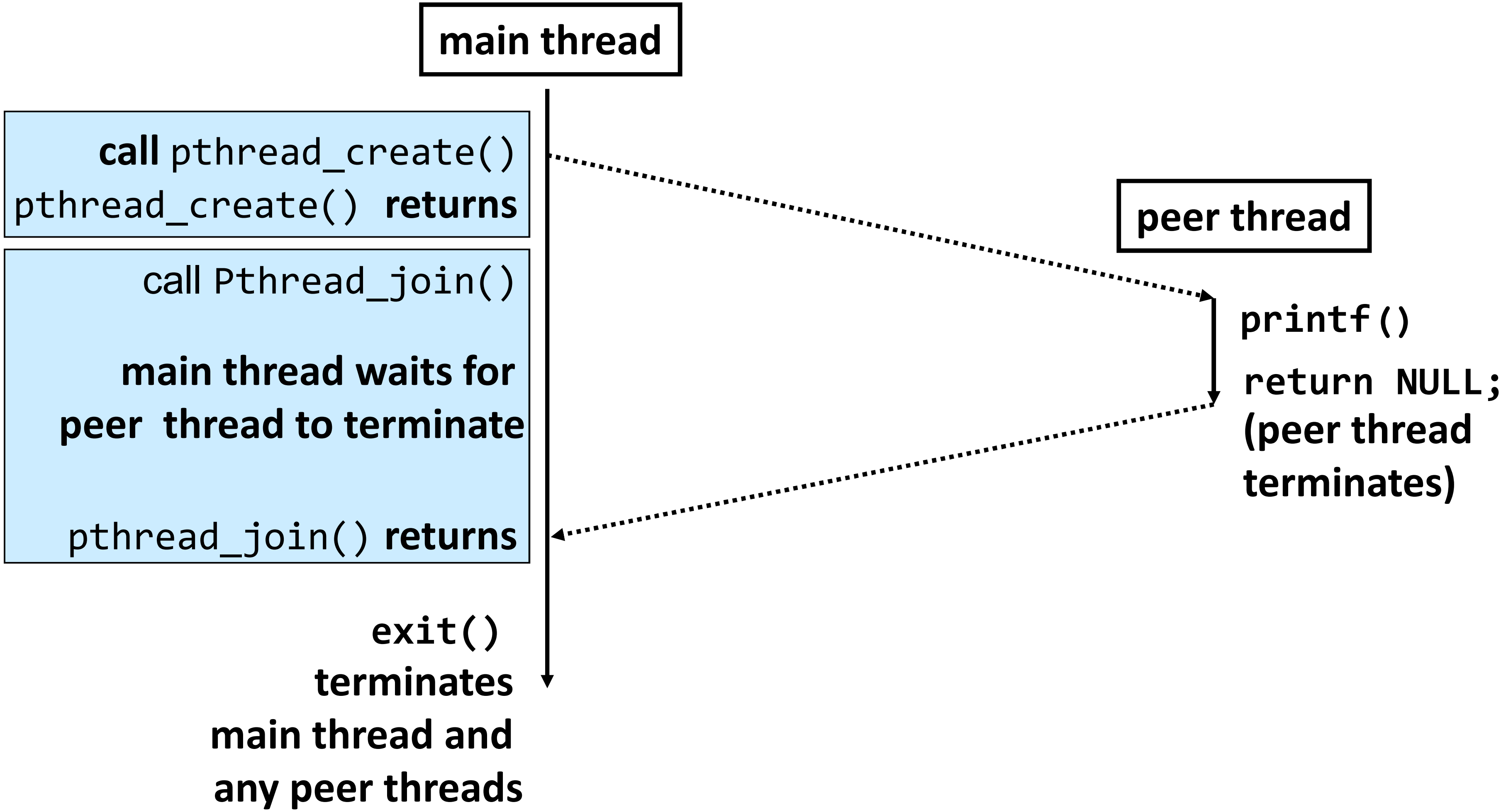
Thread attributes (usually NULL)

Thread arguments (void *p)

return value (void **p)

"hello, world" Program (2)

- **Execution of threaded "hello, world"**



Echo Server: Thread-based

```c
int main (int argc, char *argv[])
{
   int *connfdp;
   pthread_t tid;
   . . .

   while (1) {
      connfdp = (int *)
                malloc(sizeof(int));
      *connfdp = accept (listenfd,
          (struct sockaddr *)&caddr,
          &caddrlen));

      pthread_create(&tid, NULL,
          thread_main, connfdp);
   }
}
```

```c
void *thread_main(void *arg)
{
  int n;
  char buf[MAXLINE];

  int connfd = *((int *)arg);
  pthread_detach(pthread_self());
  free(arg);

  while((n = read(connfd, buf,
             MAXLINE)) > 0)
    write(connfd, buf, n);

  close(connfd);
  return NULL;
}
```

Implementation Issues (1)

- **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.
    - Exit state and return value are not saved.
  - Default state is joinable.
    - Use **pthread_detach(pthread_self())** to make detached.

Implementation Issues (2)

- **Must be careful to avoid unintended sharing**
  - For example, what happens if we pass the address connfd to the thread routine?

```
int connfd;
. . .
pthread_create(&tid, NULL, thread_main, &connfd);
. . .
```

- **All functions called by a thread must be thread-safe.**
  - A function is said to be thread-safe or reentrant, when the function may be called by more than one thread at a time without requiring any other action on the caller's part.

Thread-based Designs

- **Pros**
  - Easy to share data structures between threads.
    - e.g., logging information, file cache, etc.
  - Threads are more efficient than processes.

- **Cons**
  - 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.