Concurrent Programming:
Concurrent Servers:
3. *Thread based*

Approaches for Writing Concurrent Servers

Allow server to handle multiple clients concurrently

1. Process-based

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

2. Event-based

- Programmer manually interleaves multiple logical flows
- All flows share the same address space
- Uses technique called *I/O multiplexing*.

3. Thread-based

- Kernel automatically interleaves multiple logical flows
- Each flow shares the same address space
- Hybrid of of process-based and event-based.

Traditional View of a Process

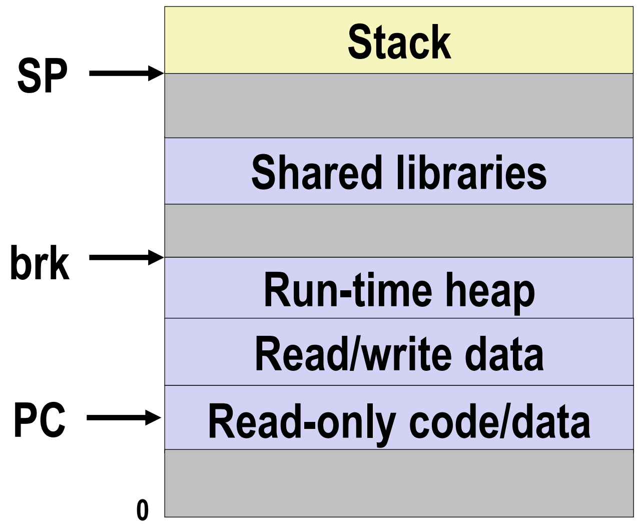
- Process = process context + code, data, and stack

Process context

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

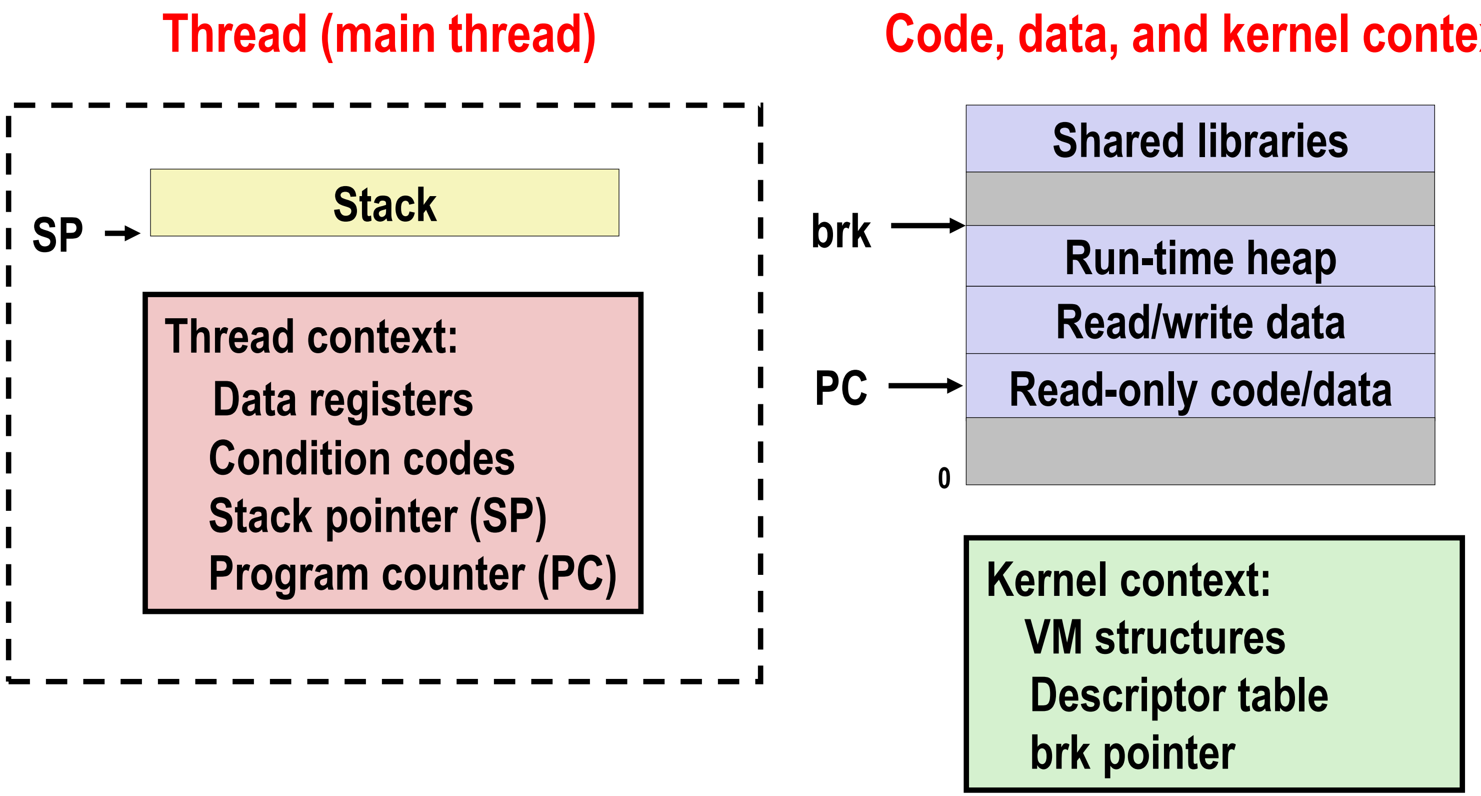
Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack



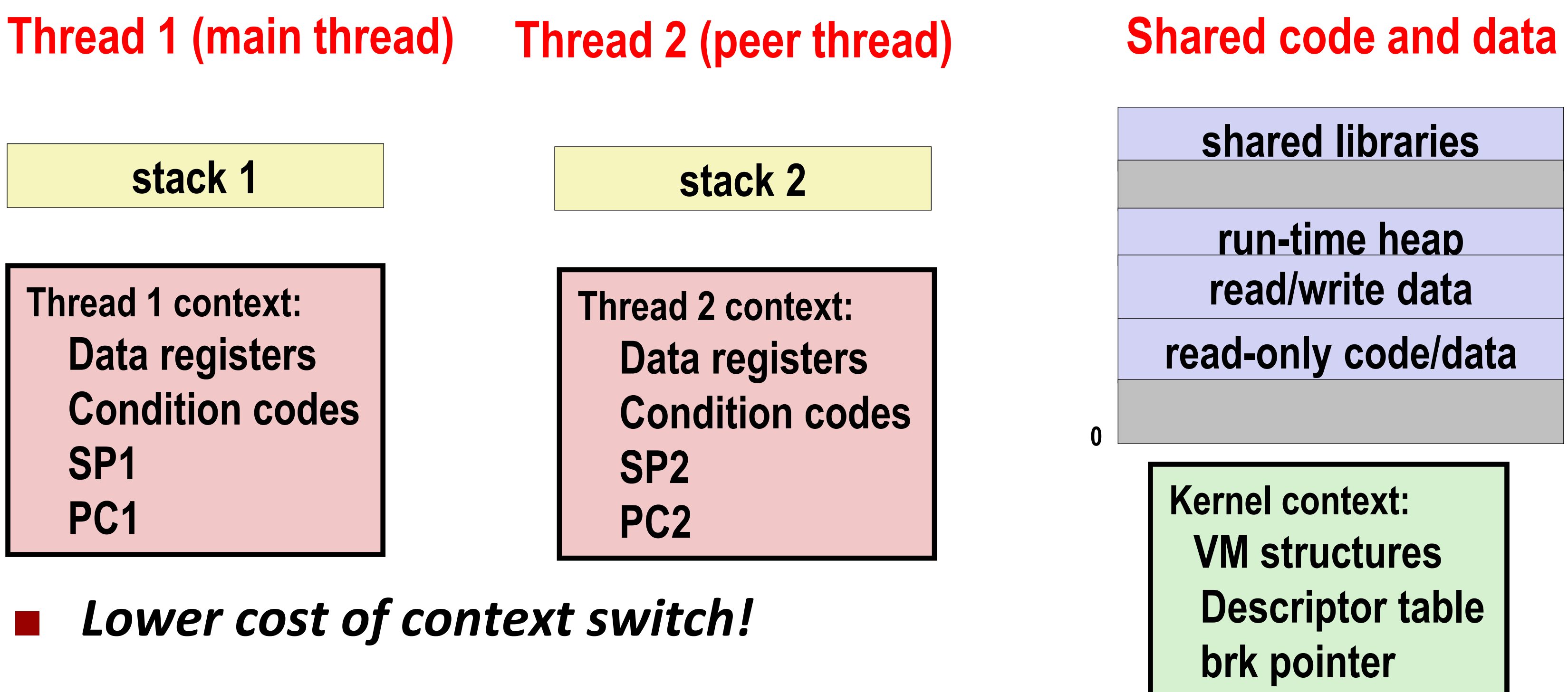
Alternate View of a Process

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



A Process With Multiple Threads

- **Multiple threads can be associated with a process**
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own logical control flow
  - Each thread has its own stack for local variables
    - but not protected from other threads
  - Each thread has its own thread id (TID), unique within process

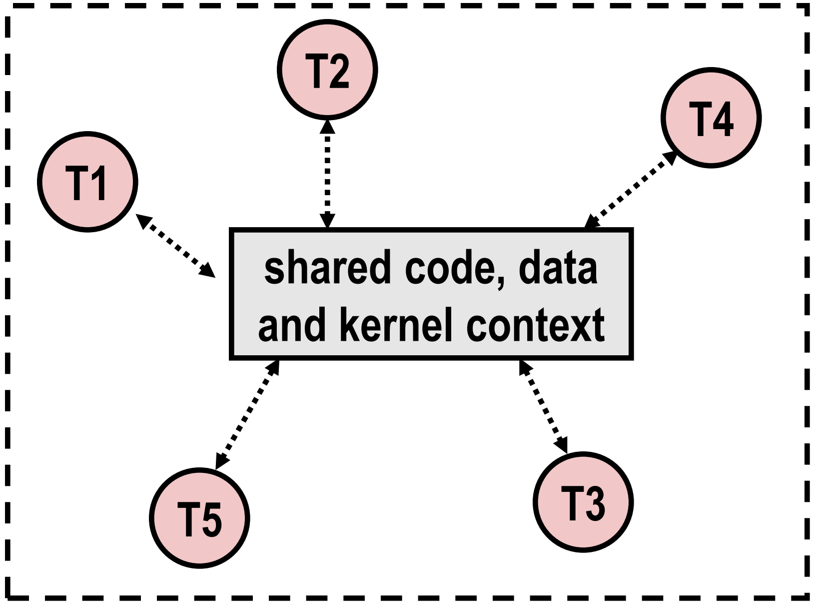


- ***Lower cost of context switch!***

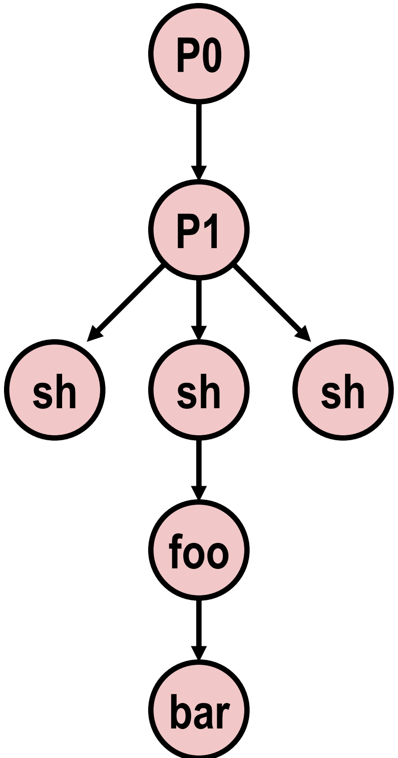
Logical View of Threads

- **Threads associated with process form a *pool* of peers**
  - Unlike processes which form a tree hierarchy
  - Possibility of mix-and-matching, but gets complex

Threads associated with process foo



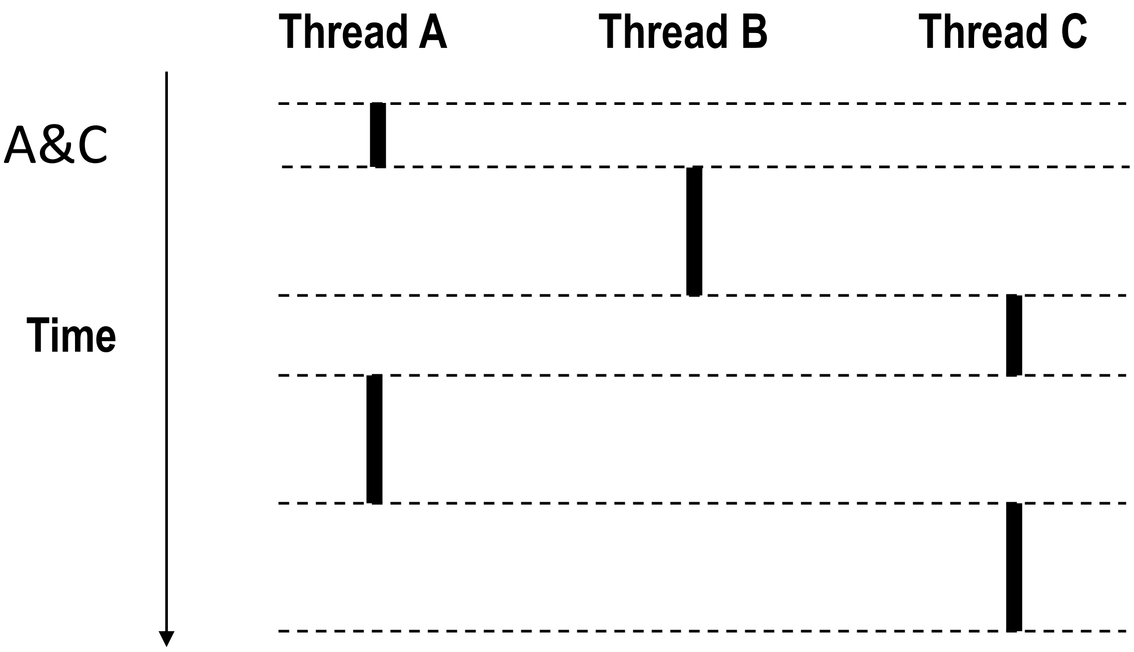
Process hierarchy



Concurrent Threads

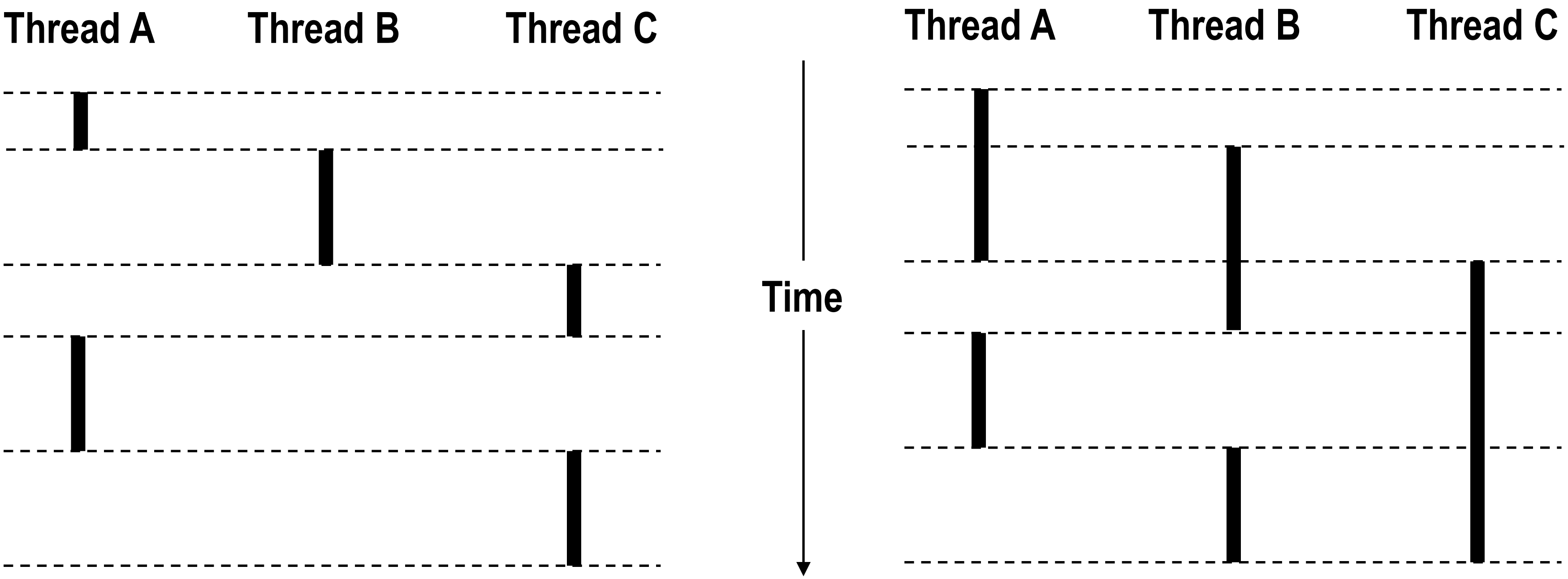
- **Two threads are *concurrent* if their flows overlap in time**
- **Otherwise, they are sequential**

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



Concurrent Thread Execution

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



Run 3 threads on 2 cores

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 all code and data (except local stacks)
    - 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 thread interface (~60 functions)**
  - Creating and reaping threads
    - `pthread_create(3)`
    - `pthread_join(3)`
  - Determining your thread ID
    - `pthread_self(3)`
  - Terminating threads
    - `pthread_cancel(3)`
    - `pthread_exit(3)`
    - `exit(3)` [terminates all threads]
  - Synchronizing access to shared variables
    - `pthread_mutex_init(3)`
    - `pthread_mutex_[un]lock(3)`
- **libc implemented `(-lpthread)`, syscall is `clone(2)`**
  - See https://nullprogram.com/blog/2015/05/15/ for raw calls

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);
}
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hello.c

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void *thread(void *vargp) /* thread routine */
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    printf("Hello, world!\n");
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Thread routine

*Thread arguments (void *p)*

*Return value (void **p)*

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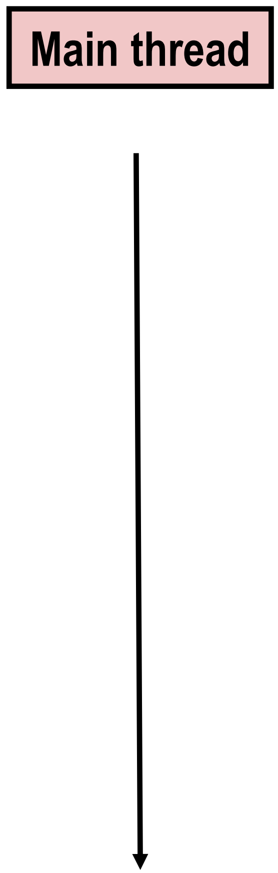
hello.c

Execution of Threaded "hello, world"



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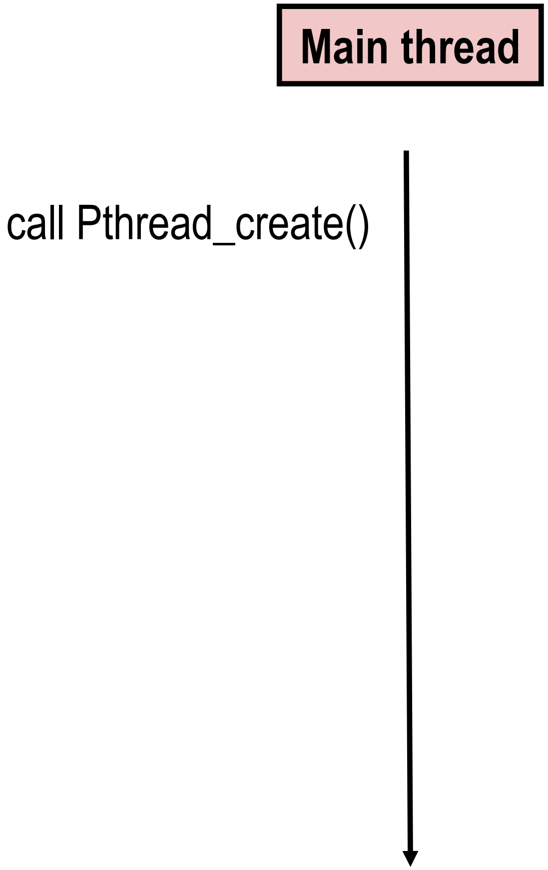

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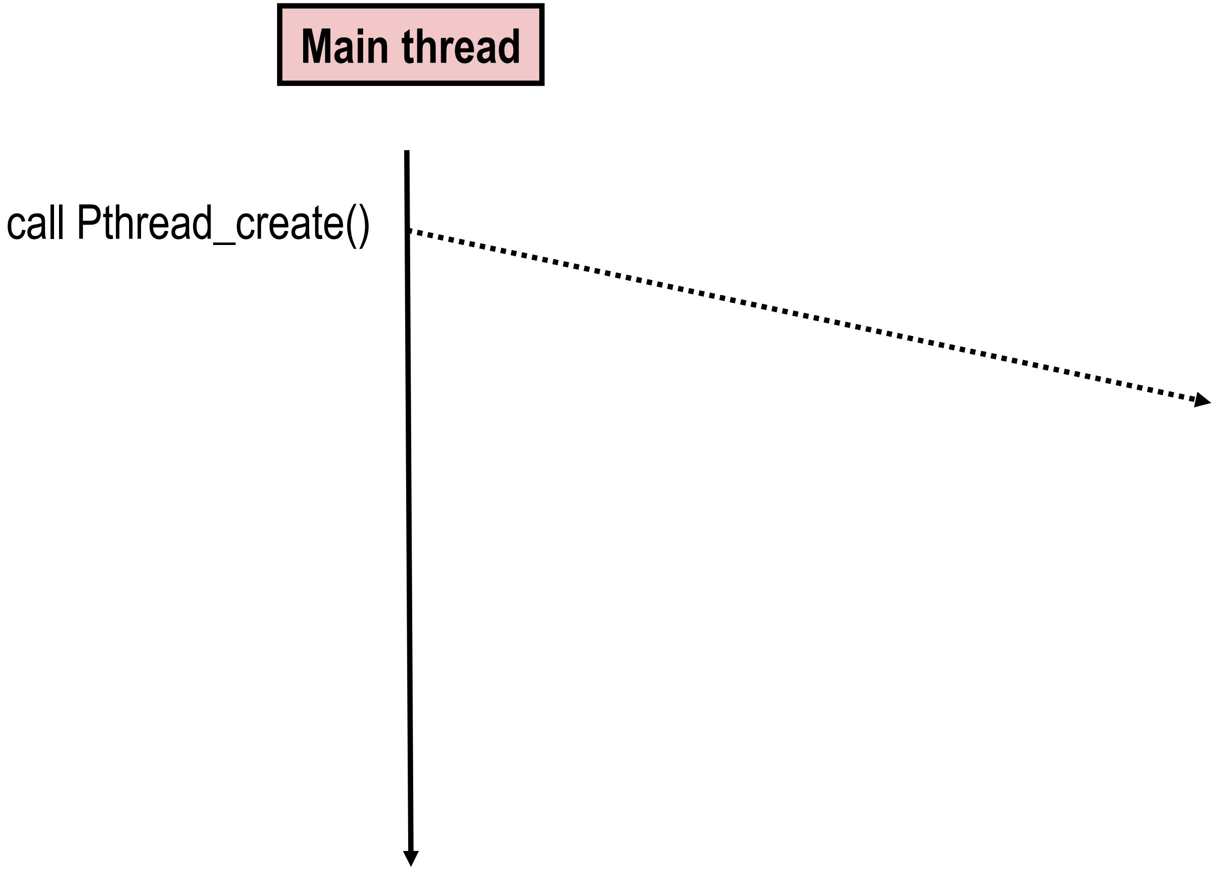

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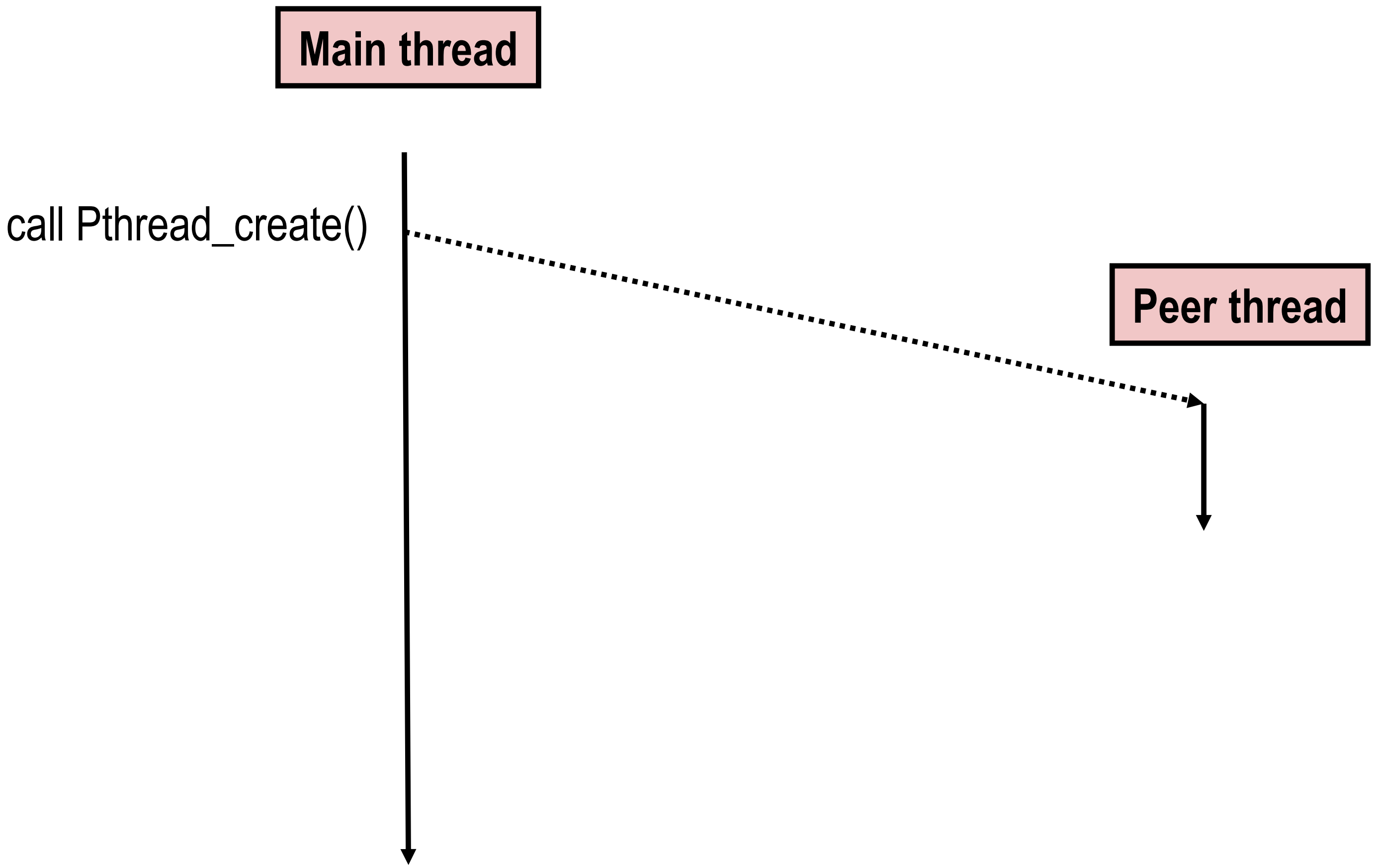

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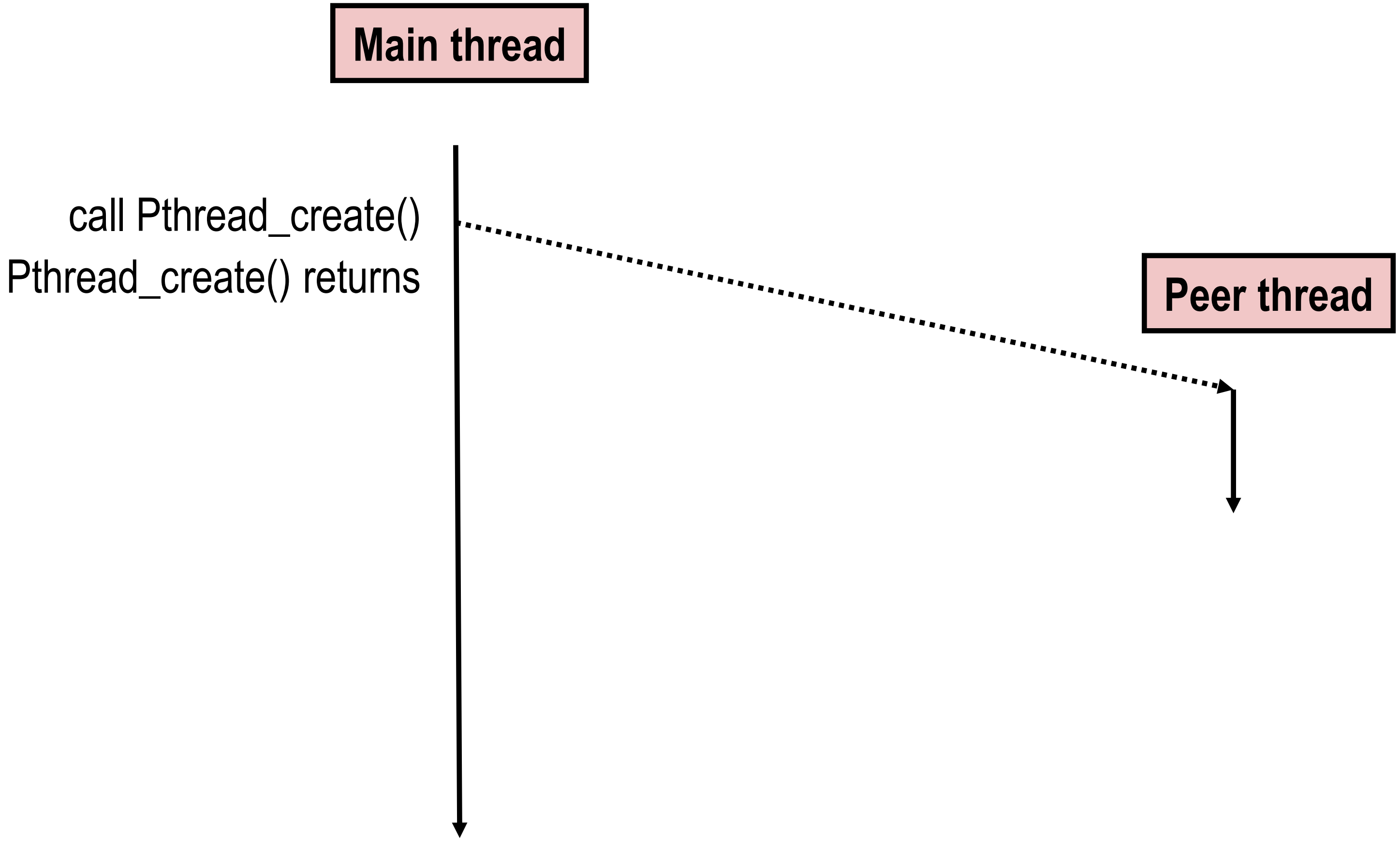

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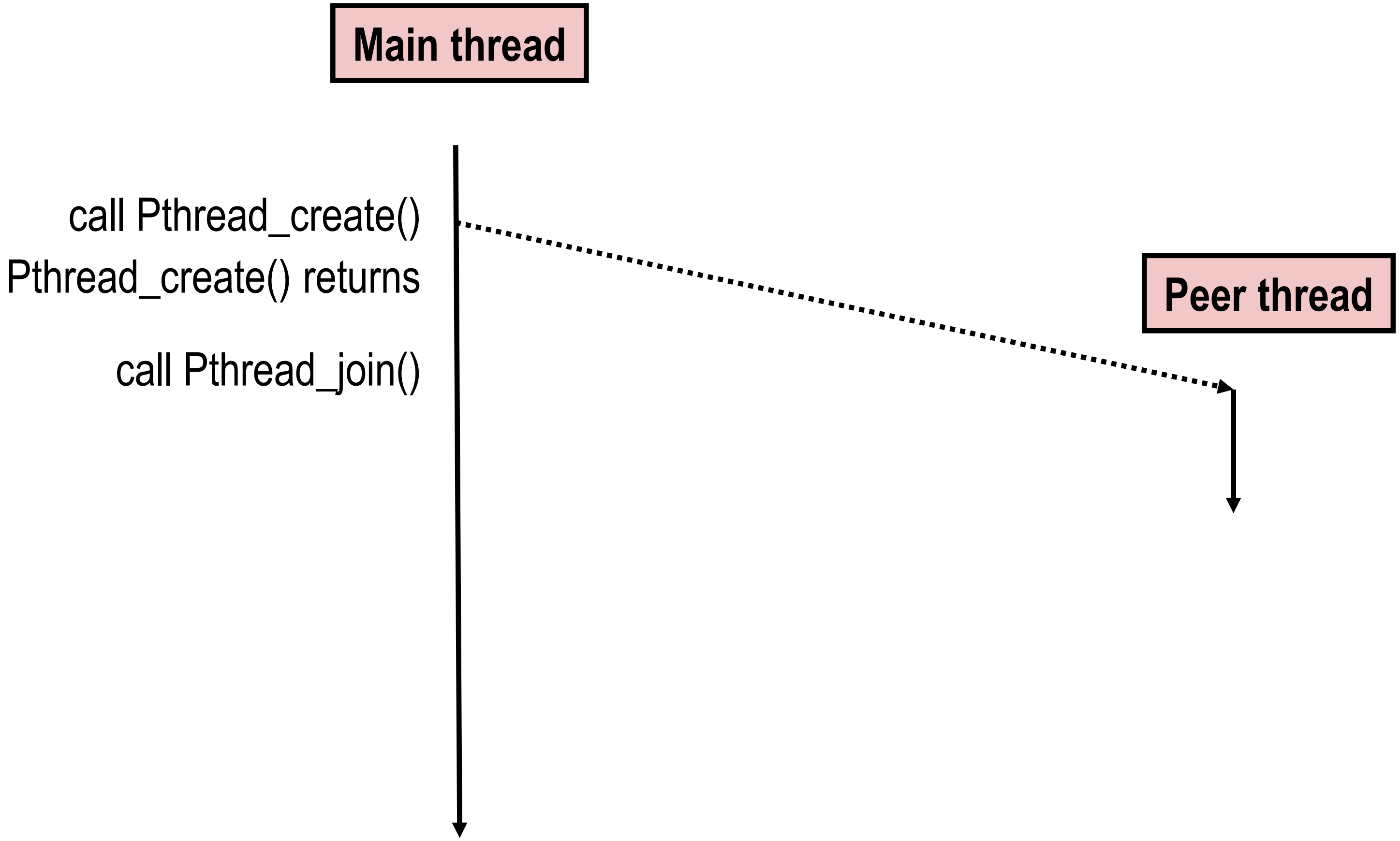

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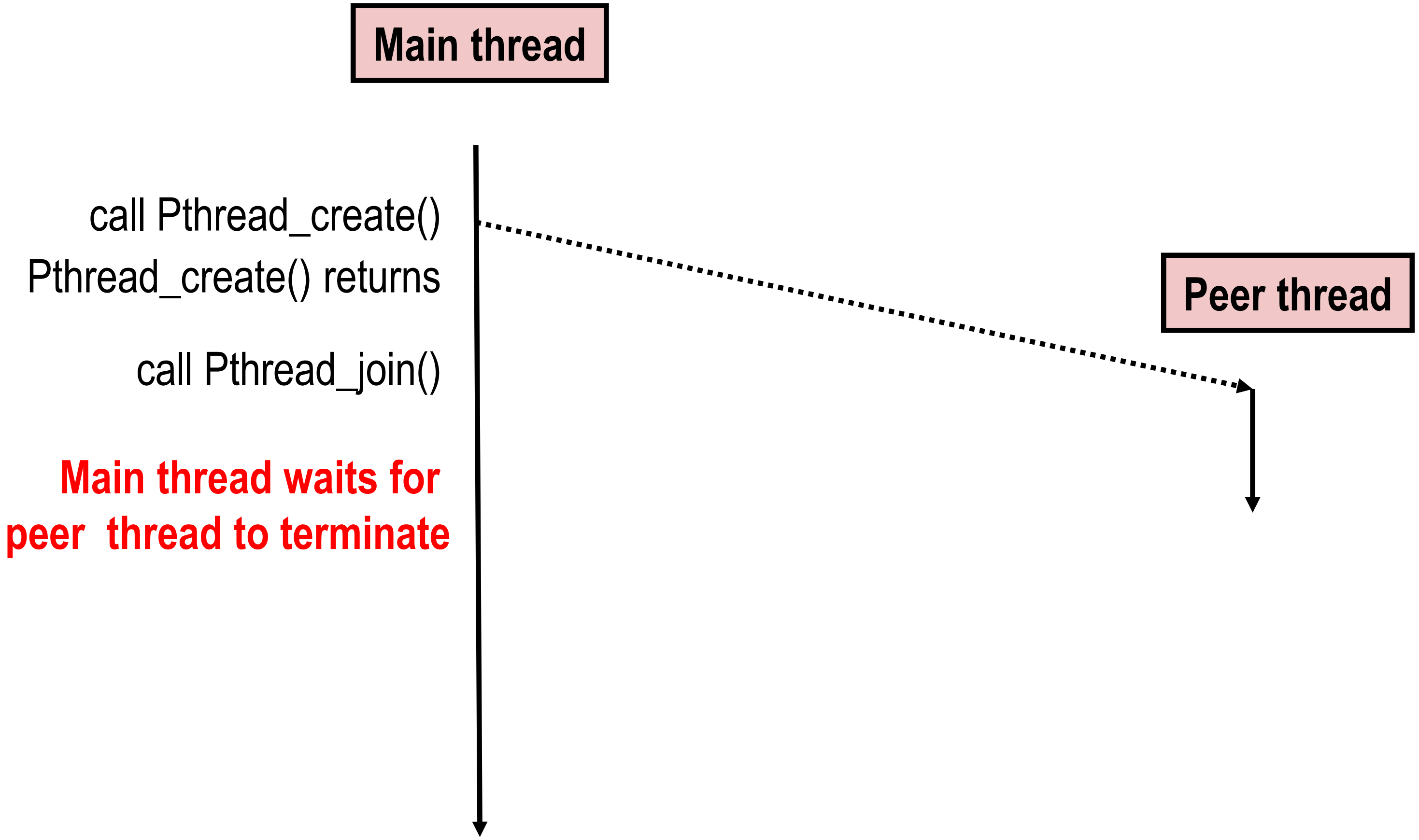

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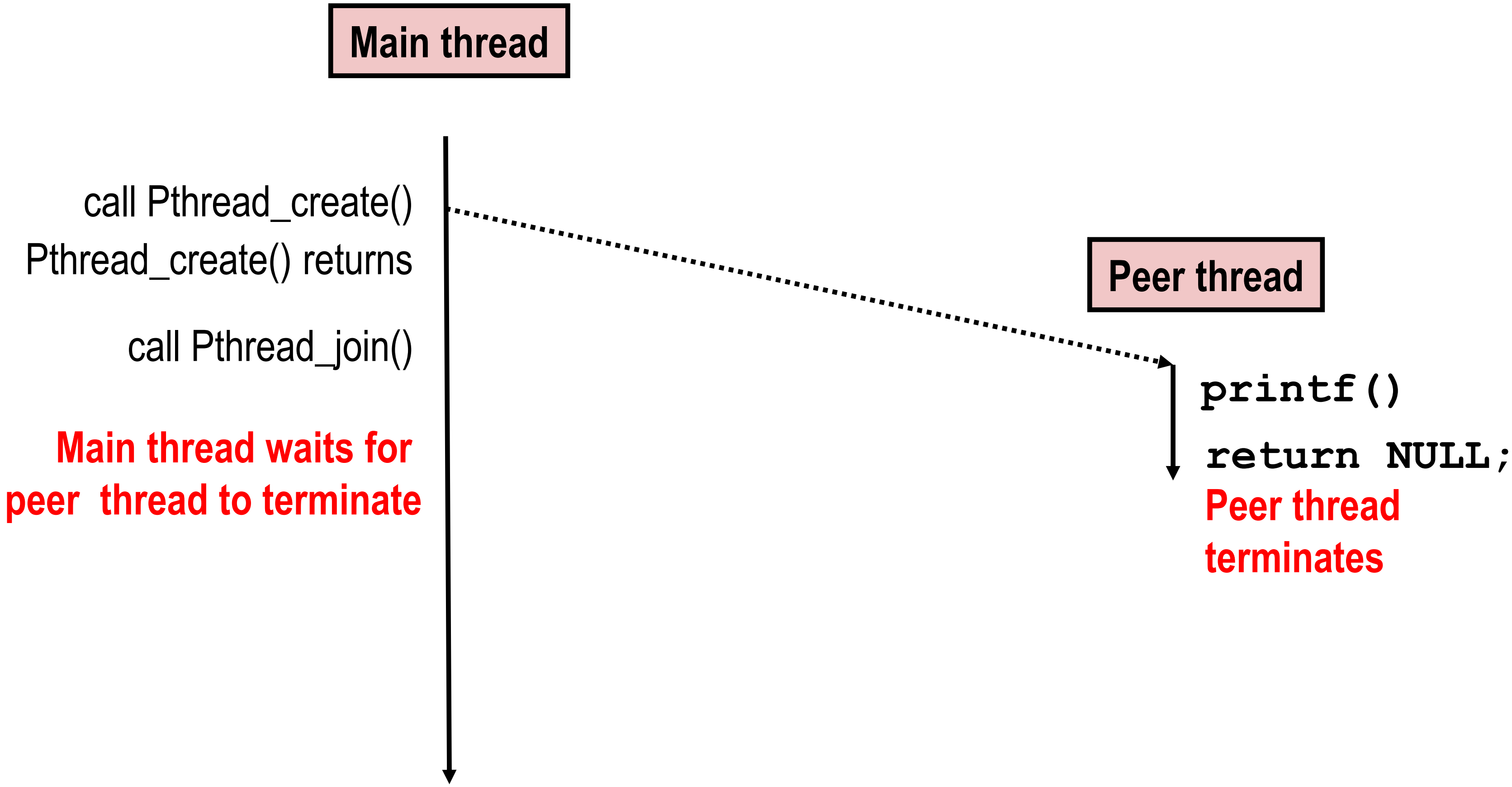

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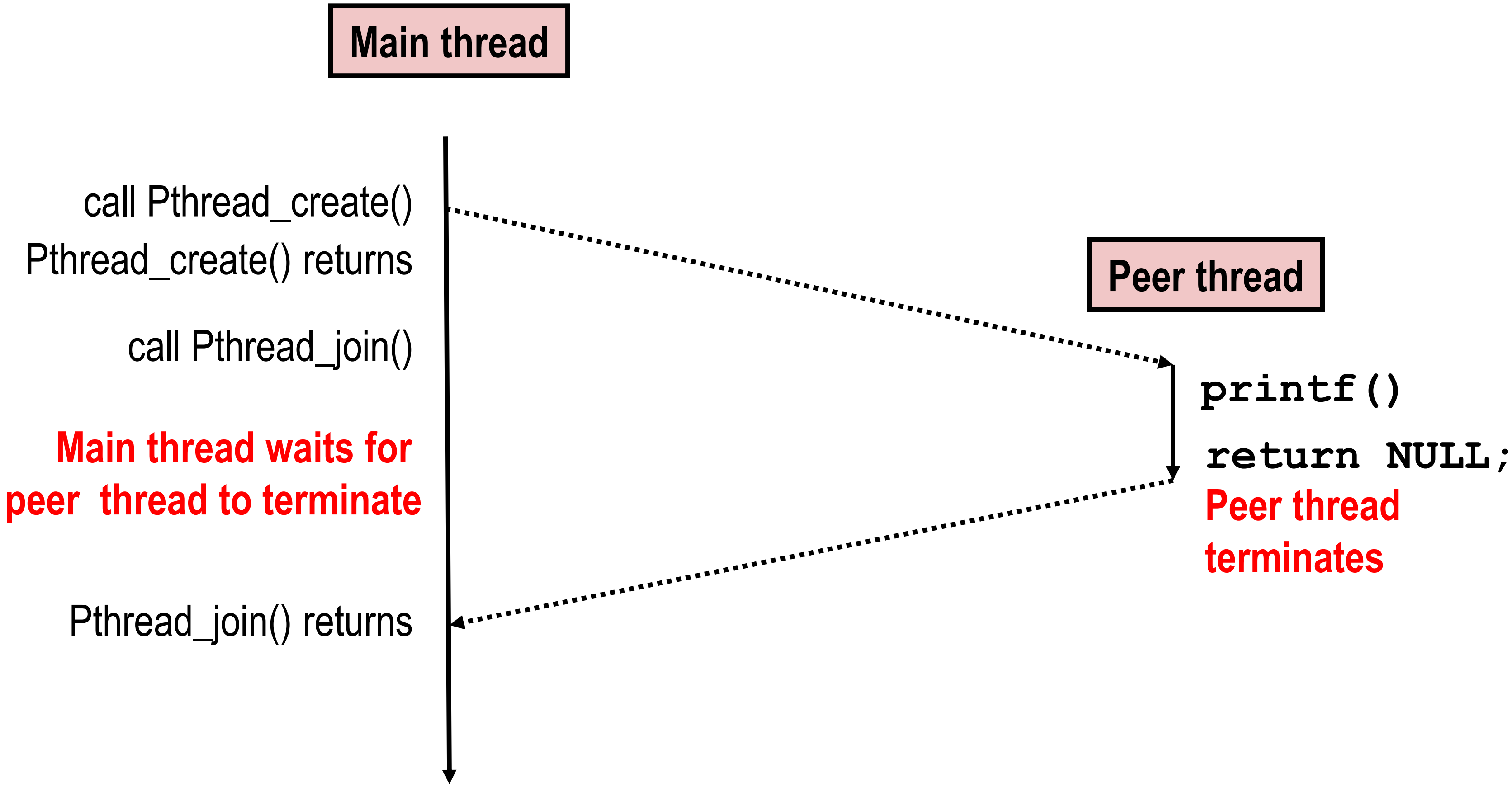

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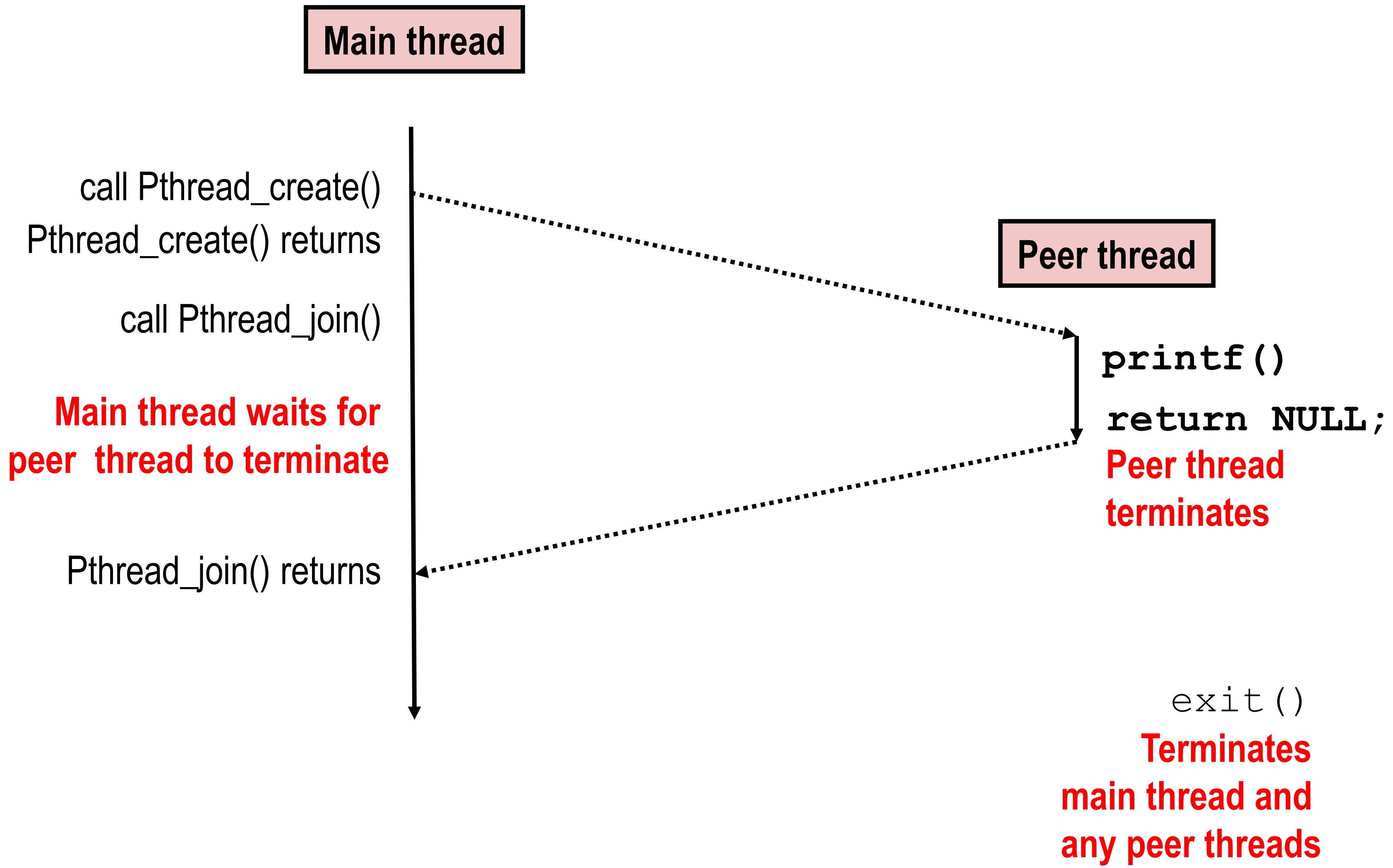


Thread-Based Concurrent Echo Server

```
int main(int argc, char **argv)
{
    int listenfd, *connfdp;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;
    pthread_t tid;

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage);
        connfdp = Malloc(sizeof(int));
        *connfdp = Accept(listenfd,
                     (SA *) &clientaddr, &clientlen);
        Pthread_create(&tid, NULL, thread, connfdp);
    }
}
```

echoservert.c

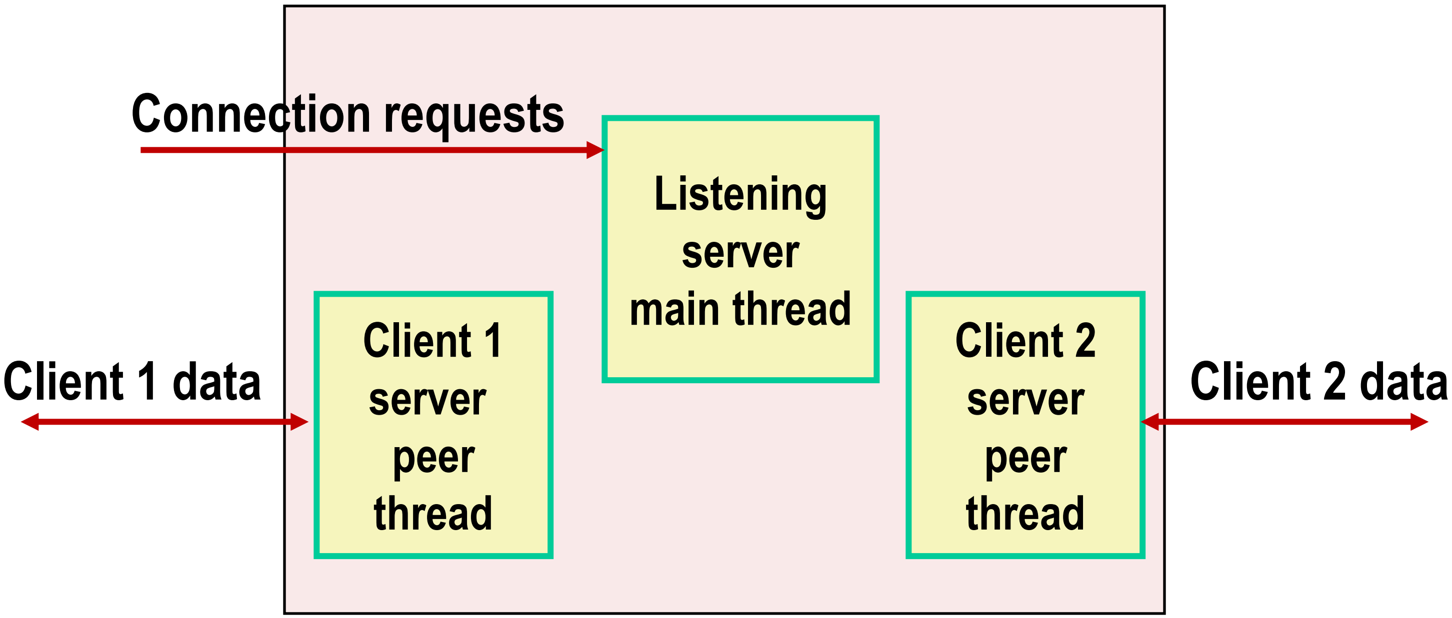
- **`malloc` of connected descriptor necessary to avoid deadly race (later)**
- **Should NOT close connfd!**

Thread-Based Concurrent Server (cont)

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

- Run thread in “detached” mode.
  - Can’t be made joinable again
  - Reaped automatically (by kernel) when it terminates
  - Either `pthread_detach` or `pthread_join` should be called for each thread, but never both!
- Must free storage allocated to hold `connfd`.
- Must close `connfd` (important, shared FD table!)

Thread-based Server Execution Model



- Each client handled by individual peer thread
- Threads share all process state in kernel, except TID
- Each thread has a separate stack for local variables, and own registers

Issues With Thread-Based Servers

- **Must join or detach**
  - 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 (useful for splitting task: “fork-join model”)
    - use `pthread_detach(pthread_self())` to make detached
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- **All functions called by a thread must be *thread-safe***
  - Much more on that later

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

Summary: Approaches to Concurrency

- **Process-based**
  - Hard to share resources/Easy to avoid unintended sharing
  - High overhead in adding and removing clients
- **Event-based**
  - 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
- **Thread-based**
  - Easy to share resources… Perhaps too easy!
  - Medium overhead
  - Not much control over scheduling policies
  - Difficult to debug
    - Event orderings not repeatable