Threads

Operating Systems
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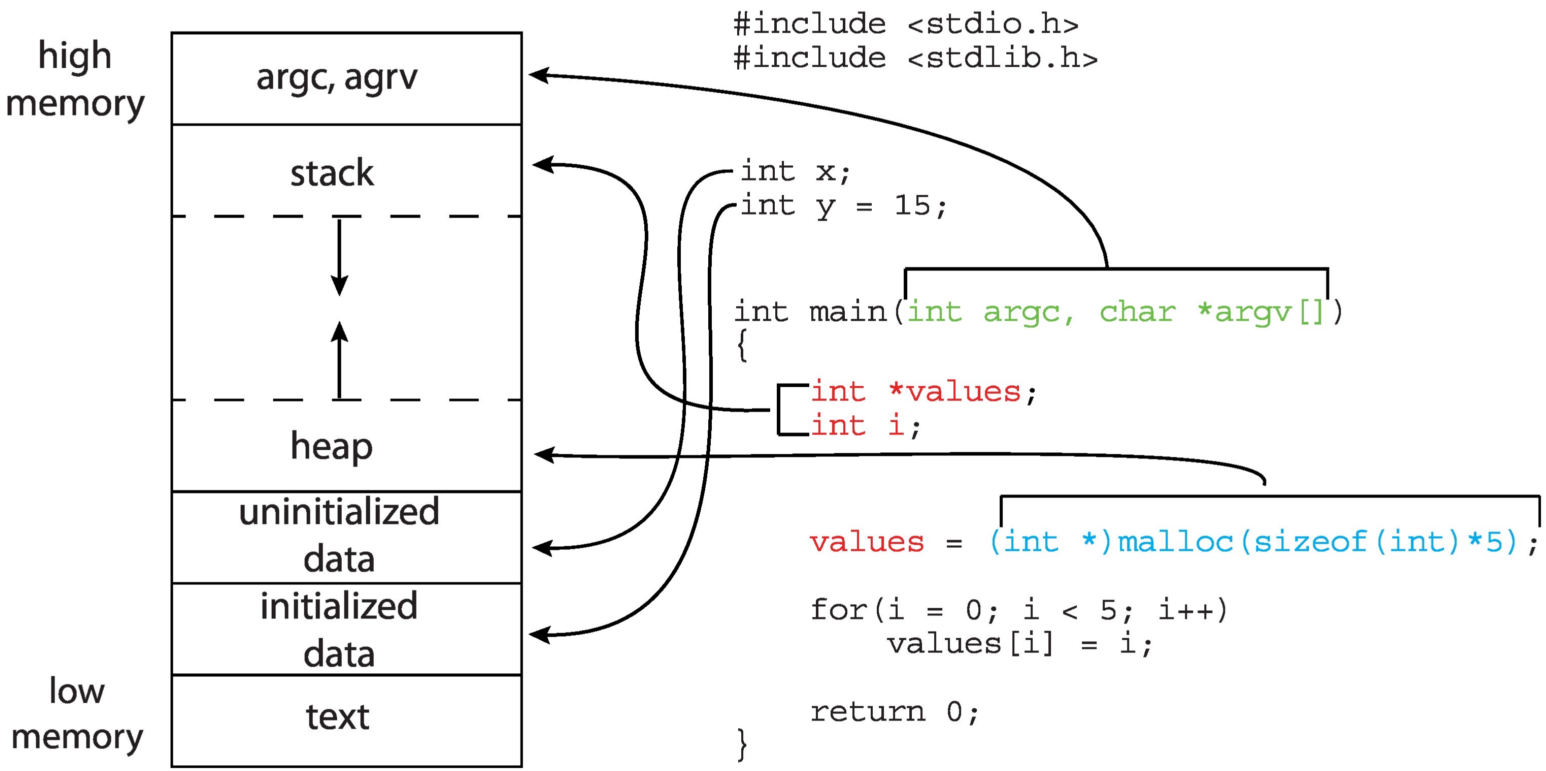
Some slides are from OSC and Henri Casanova@Hawaii

Revisit - Process Concept

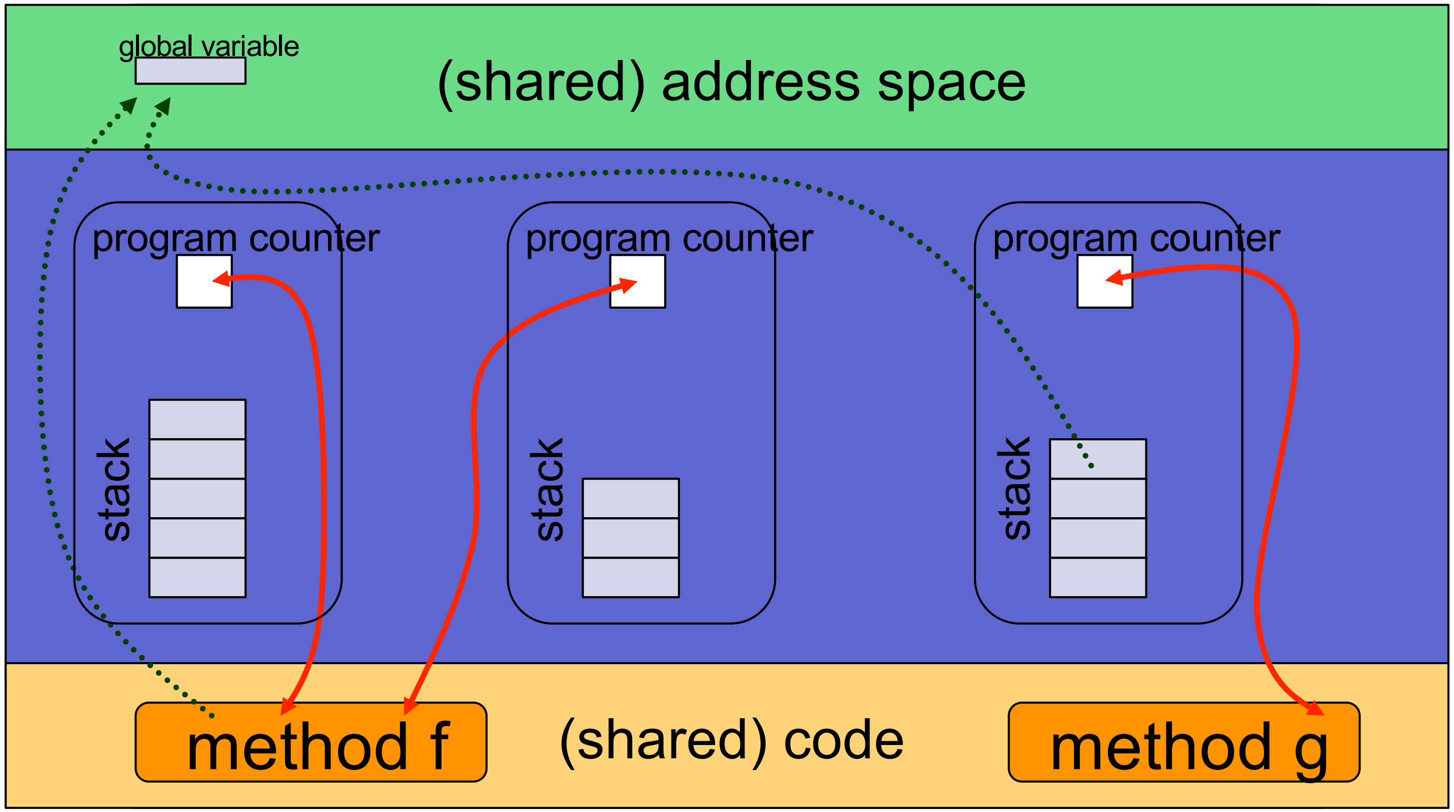
- Process =
  - code (also called the text)
    - initially stored on disk in an executable file
  - a data section
    - global variables (.bss and .data in x86 assembly)
  - program counter
    - points to the next instruction to execute (i.e., an address in the code)
  - content of the processor's registers
  - a runtime stack
  - a heap
    - for dynamically allocated memory (malloc, new, etc.)

Revisit - Memory Layout of a C Program



Why thread?

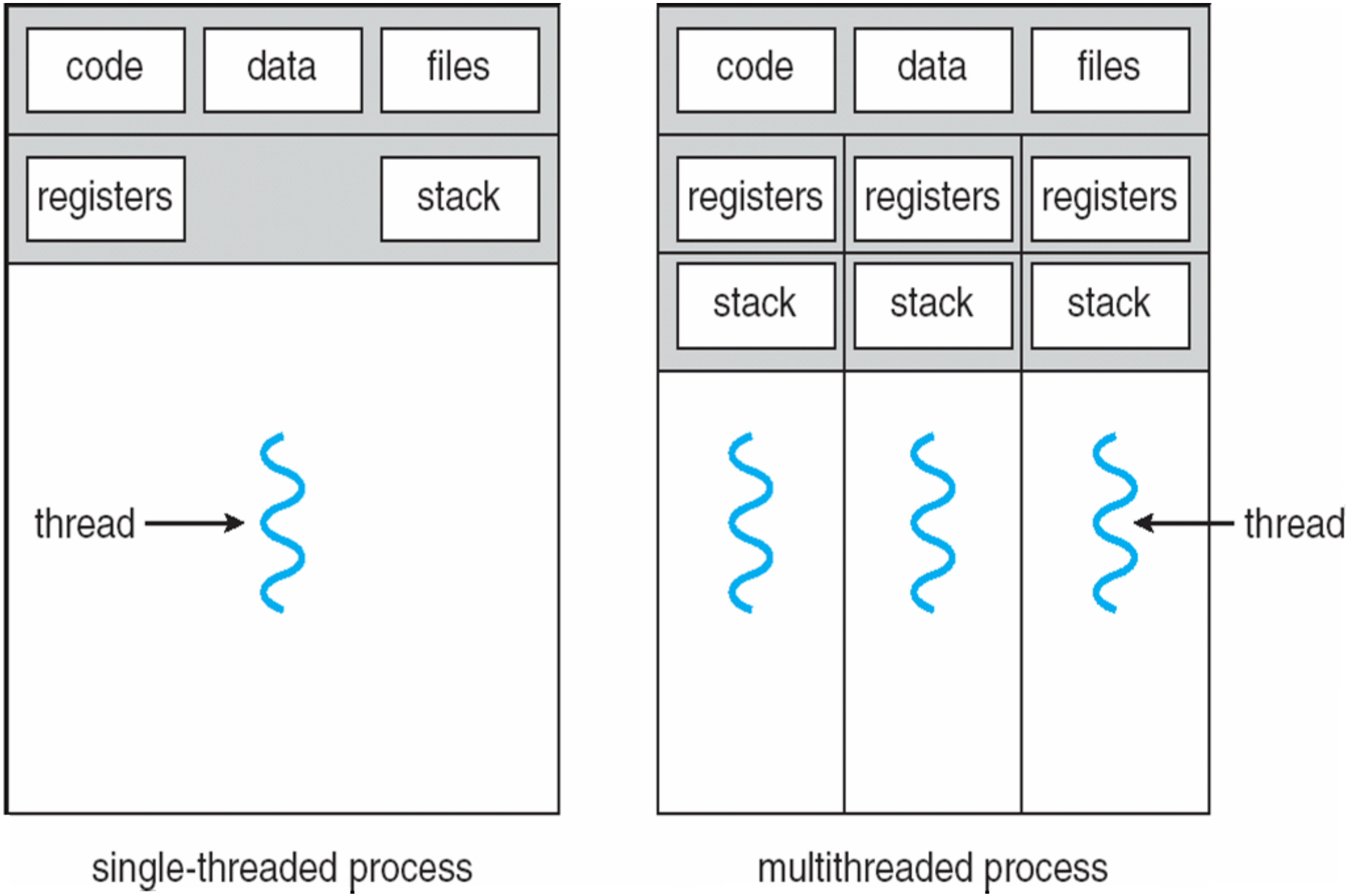
- How can we make a process run faster
  - Multiple execution units with a process



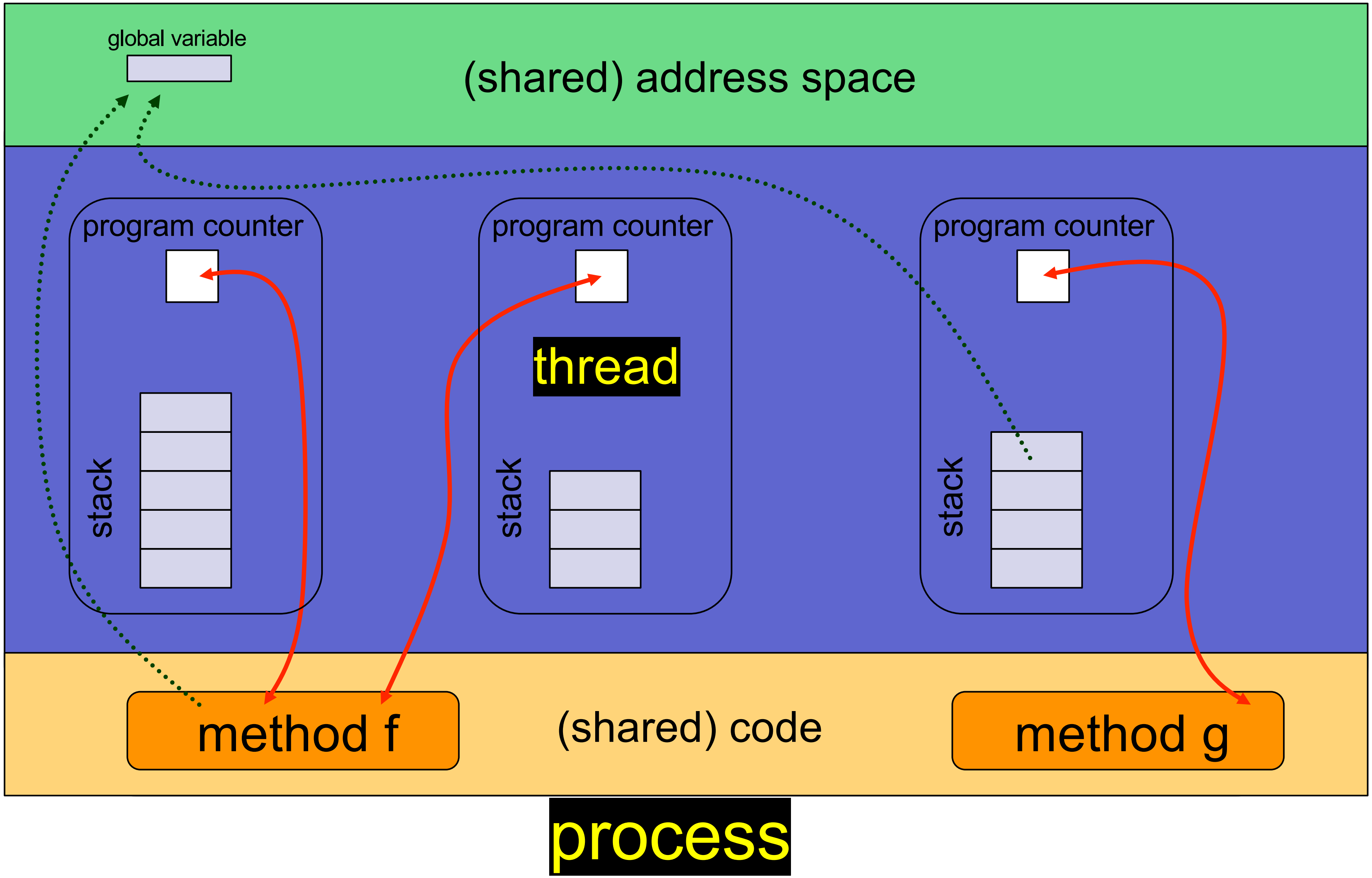
Thread Definition

- A thread is a basic unit of execution within a process
- Each thread has its own
  - thread ID
  - program counter
  - register set
  - Stack
- It shares the following with other threads within the same process
  - code section
  - data section
  - the heap (dynamically allocated memory)
  - open files and signals
- **Concurrency**: A multi-threaded process can do multiple things at once

The Typical Figure

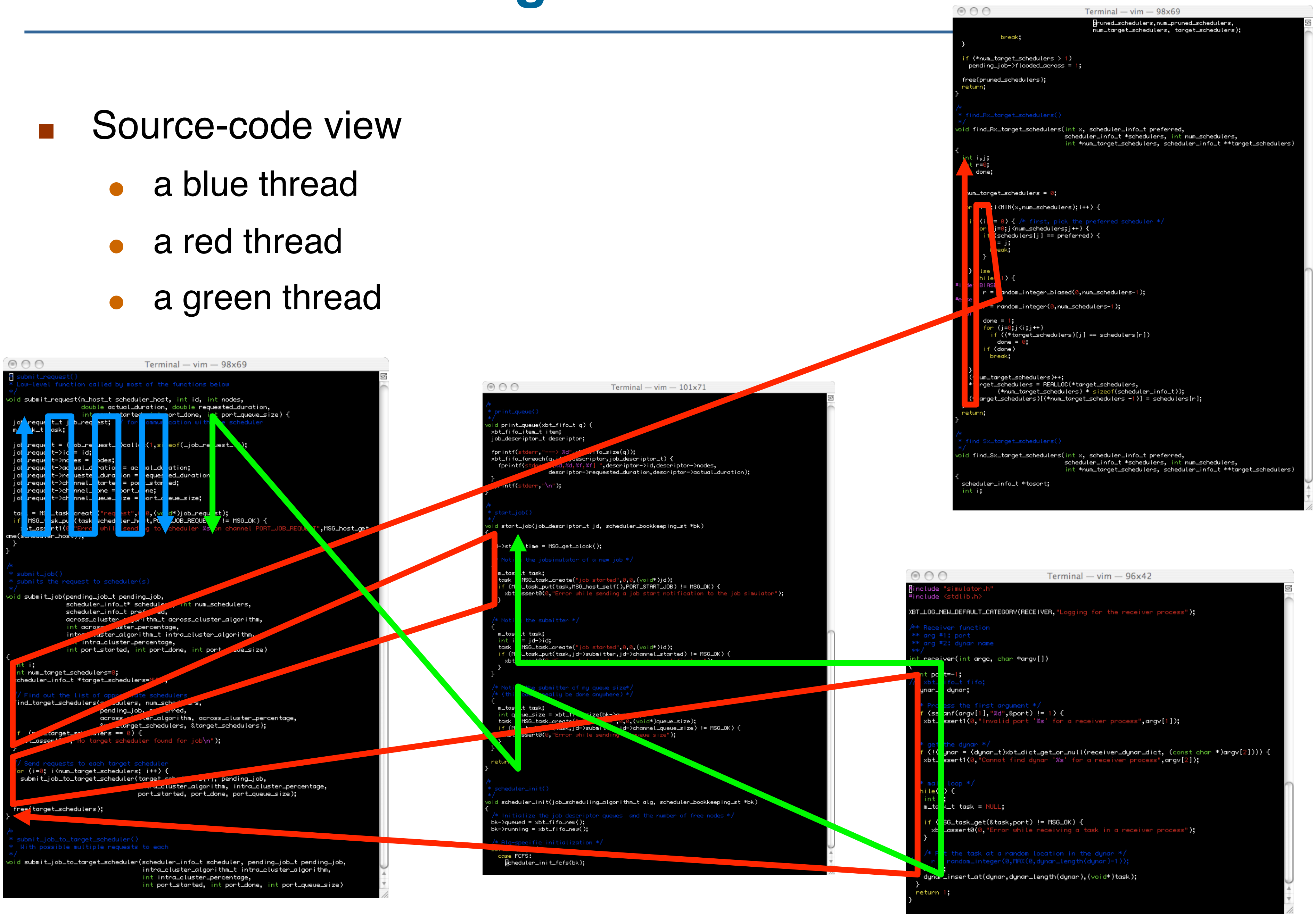


A More Detailed Figure

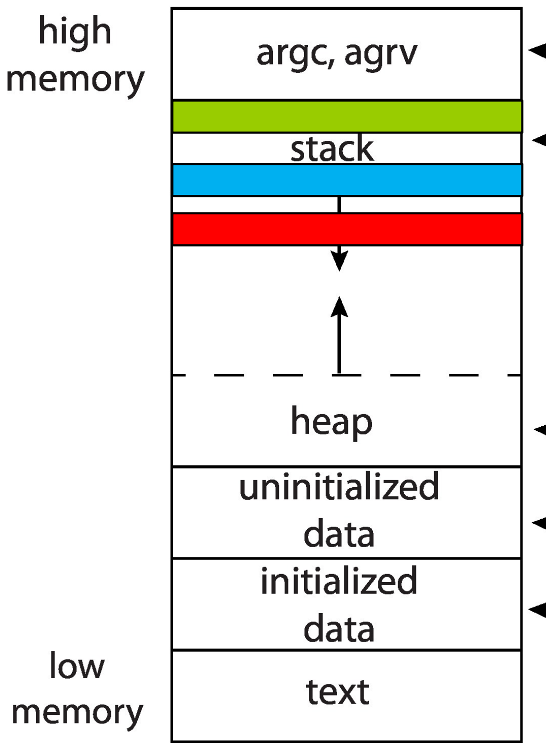


Multi-Threaded Program

- Source-code view
  - a blue thread
  - a red thread
  - a green thread



Revisit - Memory Layout of a C Program



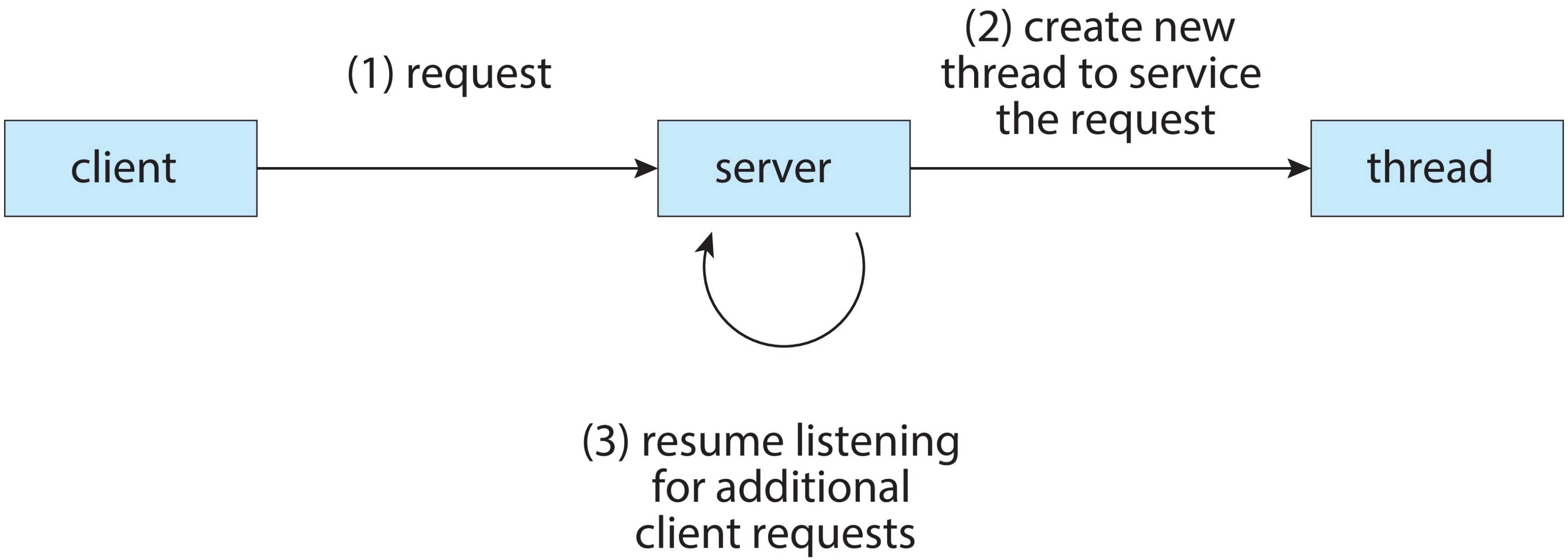

```
#include <stdio.h>
#include <stdlib.h>

int x;
int y = 15;

int main(int argc, char *argv[])
{
    int *values;
    int i;

    values = (int *)malloc(sizeof(int)*5);

    for(i = 0; i < 5; i++)
        values[i] = i;

    return 0;
}
```

Advantages of Threads?

- Economy:
  - Creating a thread is cheap
    - Much cheaper than creating a process
      - Code, data and heap are already in memory
  - Context-switching between threads is cheap
    - Much cheaper than between processes
      - No cache flush
- Resource Sharing:
  - Threads naturally share memory
    - With processes you have to use possibly complicated IPC (e.g., Shared Memory Segments)
    - IPC is not needed
  - Having concurrent activities in the same address space is very powerful
    - But fraught with danger

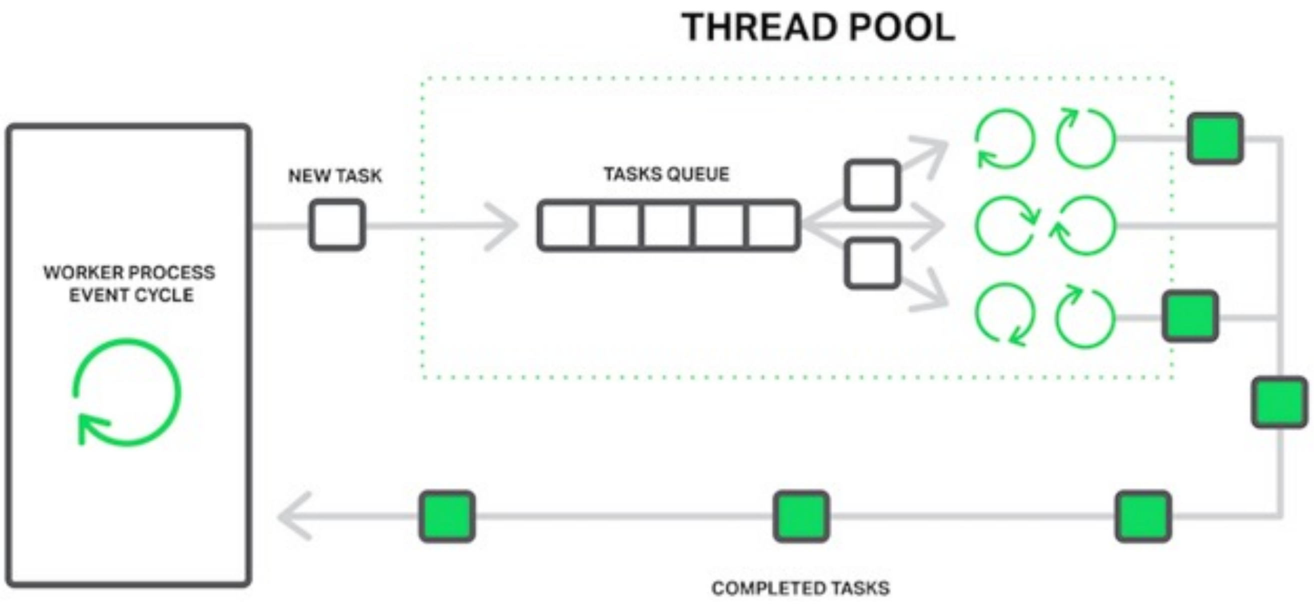
Advantages of Threads?

- Responsiveness
  - A program that has concurrent activities is more responsive
    - While one thread blocks waiting for some event, another can do something
    - e.g. Spawn a thread to answer a client request in a client-server implementation
  - This is true of processes as well, but with threads we have better sharing and economy



Advantages of Threads?

- Thread Pools in NGINX Boost Performance 9x
  - nginx : worker process -> thread pool



Advantages of Threads?

- Responsiveness
  - A program that has concurrent activities is more responsive
    - While one thread blocks waiting for some event, another can do something
    - e.g. Spawn a thread to answer a client request in a client-server implementation
  - This is true of processes as well, but with threads we have better sharing and economy
- Scalability
  - Running multiple “threads” at once uses the machine more effectively
    - e.g., on a multi-core machine
  - This is true of processes as well, but with threads we have better sharing and economy

Drawbacks of Threads

- Weak isolation between threads: If one thread fails (e.g., a segfault), then the process fails
  - And therefore the whole program
- This leads to process-based concurrency
  - e.g., The Google Chrome Web browser
  - See http://www.google.com/googlebooks/chrome/
- Sort of a throwback to the pre-thread era
  - Threads have been available for 20+ years
  - Very trendy recently due to multi-core architectures

Drawbacks of Threads

- Threads may be more memory-constrained than processes
  - Due to OS limitation of the address space size of a single process
  - Not a problem any more on 64-bit architecture
- Threads do not benefit from memory protection
  - Concurrent programming with threads is hard
    - But so is it with Processes and Shared Memory Segments

Threads on My Machine?

- Let's run ps aux and look at several applications
  - ps -eLf
  - Firefox
  - Terminal
  - ...

Multi-Threading Challenges

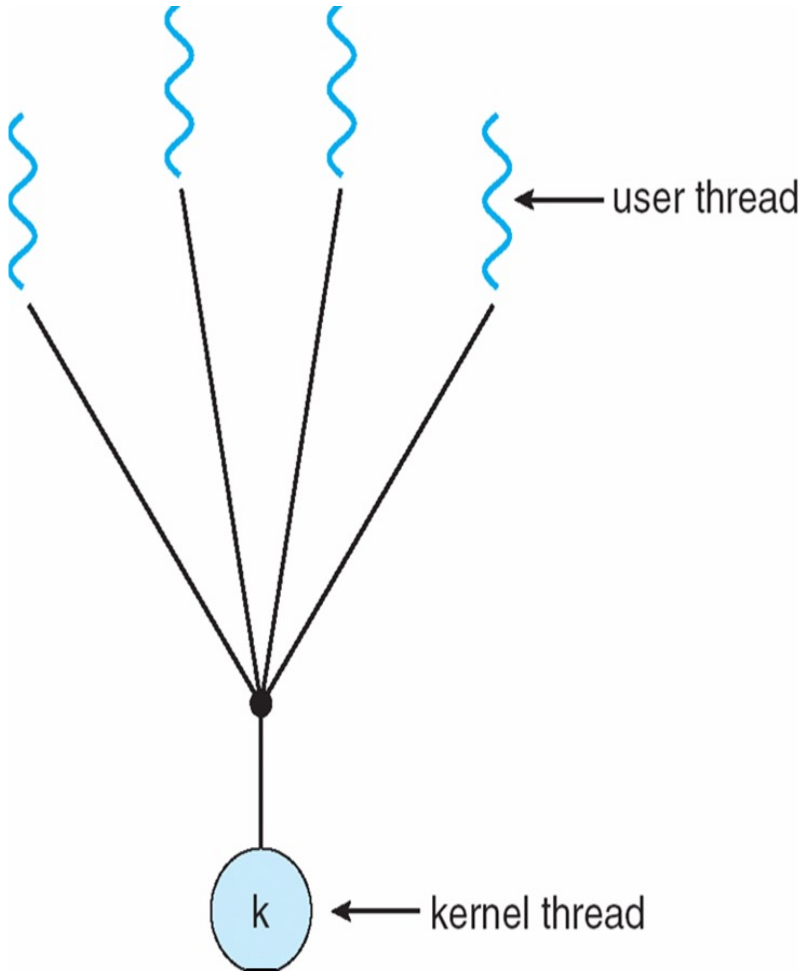
- Typical challenges of multi-threaded programming
  - Deal with data dependency and synchronization
  - Dividing activities among threads
  - Balancing load among threads
  - Split data among threads
  - Testing and debugging

User Threads vs. Kernel Threads

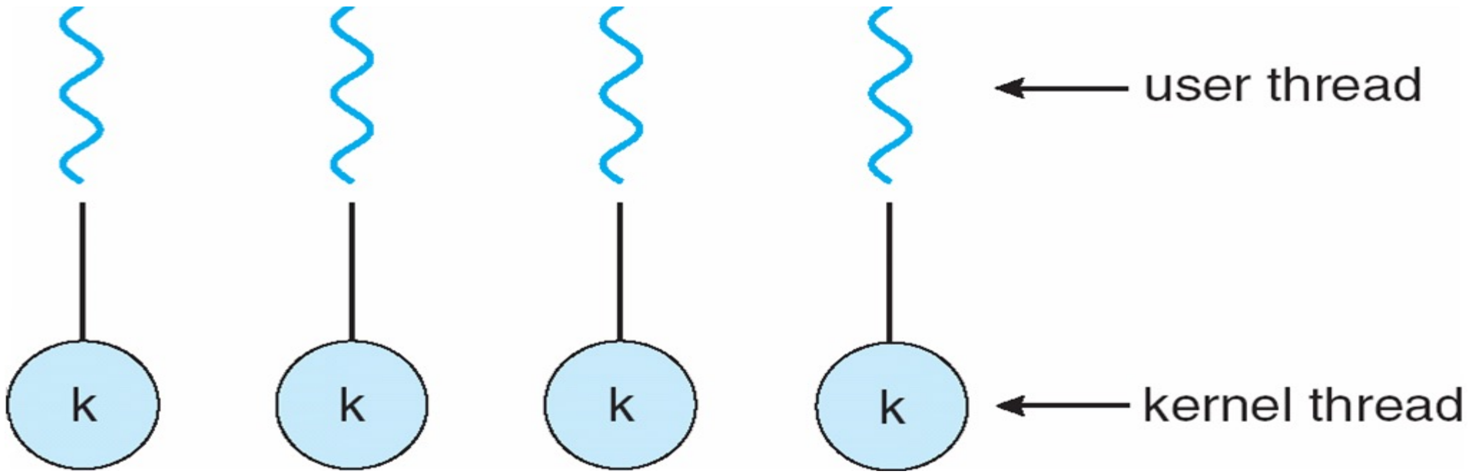
- Threads can be supported solely in User Space
  - Threads are managed by some user-level thread library (e.g., Java Green Threads)
- Threads can also be supported in Kernel Space
  - The kernel has data structure and functionality to deal with threads
  - Most modern OSes support kernel threads
    - In fact, Linux doesn't really make a difference between processes and threads (same data structure)

Many-to-One Model

- Advantage: multi-threading is efficient and low-overhead
  - No syscalls to the kernel
- Major Drawback #1: cannot take advantage of a multi-core architecture!
- Major Drawback #2: if one threads blocks, then all the others do!
- Examples (User-level Threads):
  - Java Green Threads
  - GNU Portable Threads



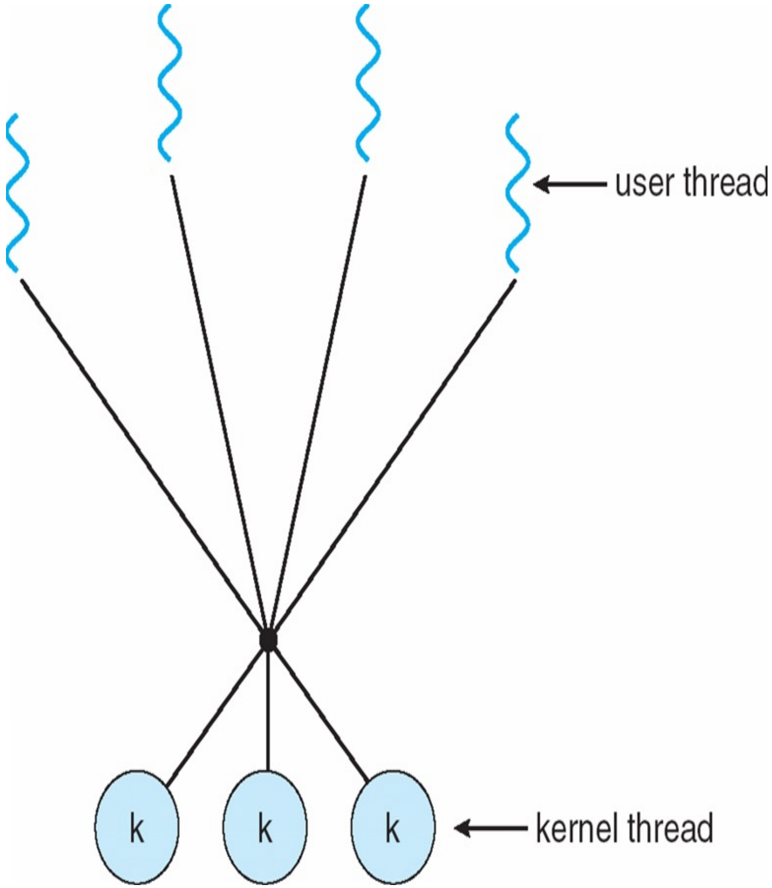
One-to-One Model



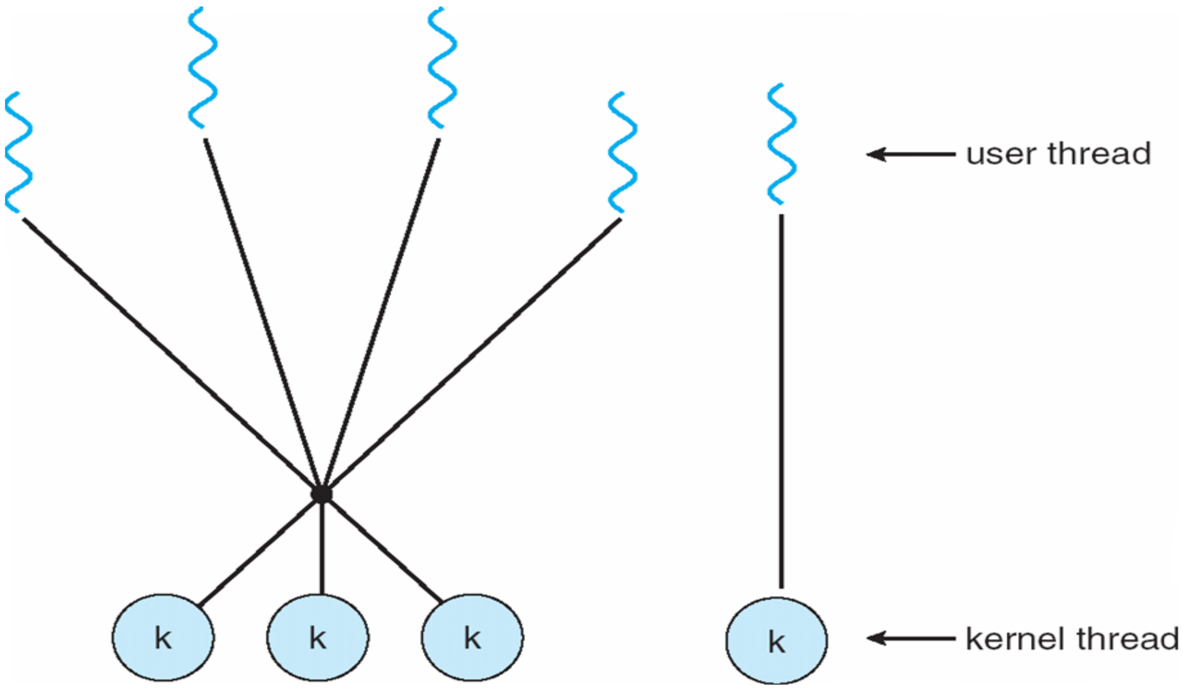
- Removes both drawbacks of the Many-to-One Model
- Creating a new threads requires work by the kernel
  - Not as fast as in the Many-to-One Model
- Example:
  - Linux
  - Windows
  - Solaris 9 and later

Many-to-Many Model

- A compromise
- If a user thread blocks, the kernel can create a new kernel threads to avoid blocking all user threads
- A new user thread doesn't necessarily require the creation of a new kernel thread
- True concurrency can be achieved on a multi-core machine
- Examples:
  - Solaris 9 and earlier
  - Win NT/2000 with the ThreadFiber package



Two-Level Model



- The user can say: “Bind this thread to its own kernel thread”
- Example:
  - IRIX, HP-UX, Tru64 UNIX
  - Solaris 8 and earlier

Thread Libraries

- Thread libraries provide users with ways to create threads in their own programs
  - In C/C++: pthreads and Win32 threads
    - Implemented by the kernel
  - In C/C++: OpenMP
    - A layer above pthreads for convenient multithreading in “easy” cases
  - In Java: Java Threads
    - Implemented by the JVM, which relies on threads implemented by the kernel

Pthreads

- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
- ***Specification***, not ***implementation***
- API specifies behavior of the thread library, implementation is up to development of the library
- Common in UNIX operating systems (Linux & Mac OS X)

Pthreads Example

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
int sum; /* this data is shared by the thread(s) */

/* The thread will execute in this function */
void *runner(void *param) {
     int i, upper = atoi(param);
     sum = 0;

     for (i = 1; i <= upper; i++)
          sum += 1;
     pthread_exit(0);
}

int main(int arge, char *argv[]) {
     pthread_t tid; /* the thread identifier */
     pthread_attr_t attr; /* set of thread attributes */

     /* set the default attributes of the thread */
     pthread_attr_init(&attr);

     /* create the thread */
     pthread_create(&tid, &attr, runner, argv[1]);

     /* wait for the thread to exit */
     pthread_join(tid, NULL);

     printf("sum = %d\n", sum);
}
```

Pthreads Code for Joining 10 Threads

```
#define NUM THREADS 10

/* an array of threads to be joined upon */
pthread_t workers[NUM_THREADS];

for (int i = 0; 1 < NUM THREADS; i++)
    pthread_join(workers[i], NULL);
```

Windows Multithreaded C Program

```
#include <windows.h>
#include <stdio.h>
DWORD Sum; /* data is shared by the thread(s) */

/* The thread will execute in this function */
DWORD WINAPI Summation(LPVOID Param){
    DWORD Upper = *(DWORD *)Param;
    for (DWORD i = 1; i ≤ Upper; i++)
        Sum += i;
    return 0;
}

int main(int argc, char *argv[])
{
    DWORD ThreadId;
    HANDLE ThreadHandle;
    int Param;

    Param = atoi(argv[1]);

    /* create the thread */
    ThreadHandle = CreateThread(NULL, 0,
        Summation, /* thread function */
        &Param, /* parameter to thread function */
        0, &ThreadId); /* returns the thread identifier */

    /* now wait for the thread to finish */
    WaitForSingleObject(ThreadHandle, INFINITE);

    /* close the thread handle */ CloseHandle(ThreadHandle);
    printf("sum = %d\n", Sum);
}
```

OpenMP

- Set of compiler directives and an API for C, C++, FORTRAN
- Provides support for parallel programming in shared-memory environments
- Identifies **parallel regions** – blocks of code that can run in parallel

`#pragma omp parallel`

Create as many threads as there are cores

```
#include <omp.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
     /* sequential code */

     #pragma omp parallel
     {
     printf("I am a parallel region.");
     }

     /* sequential code */
     return 0;
}

#pragma omp parallel for
for (i = 0; i < N; i++)
{
     c[i] = a[i] + b[i];
}
```

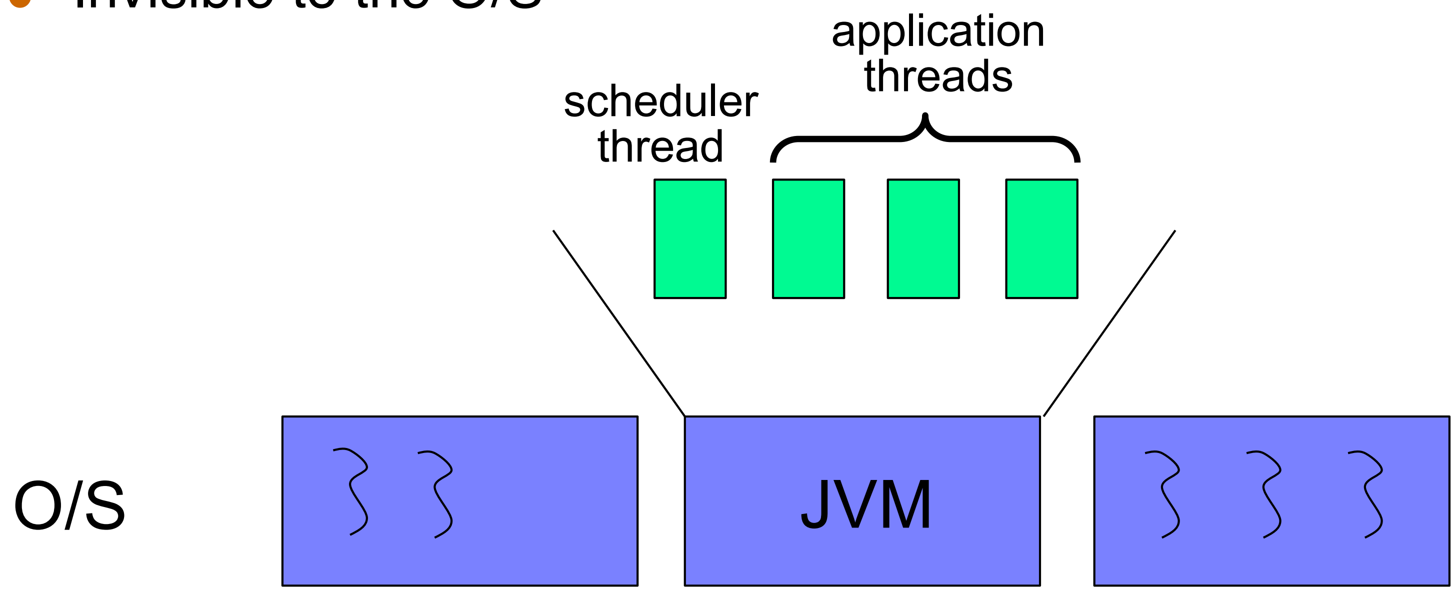
Java Threads

- All memory-management headaches go away with Java Threads
  - In nice Java fashion
- Several programming languages have long provided constructs/abstractions for writing concurrent programs
  - Modula, Ada, etc.
- Java threads may be created by:
  - Extending Thread class
  - Implementing the Runnable interface

```
class MyThread extends Thread {
     public void run() {
          . . .
     }
}
MyThread t = new MyThread();

public interface Runnable {
     public abstract void run();
}
```

Thread Scheduling

- The JVM keeps track of threads, enacts the thread state transition diagram
- Question: who decides which runnable thread to run?
- Old versions of the JVM used Green Threads
  - User-level threads implemented by the JVM
  - Invisible to the O/S

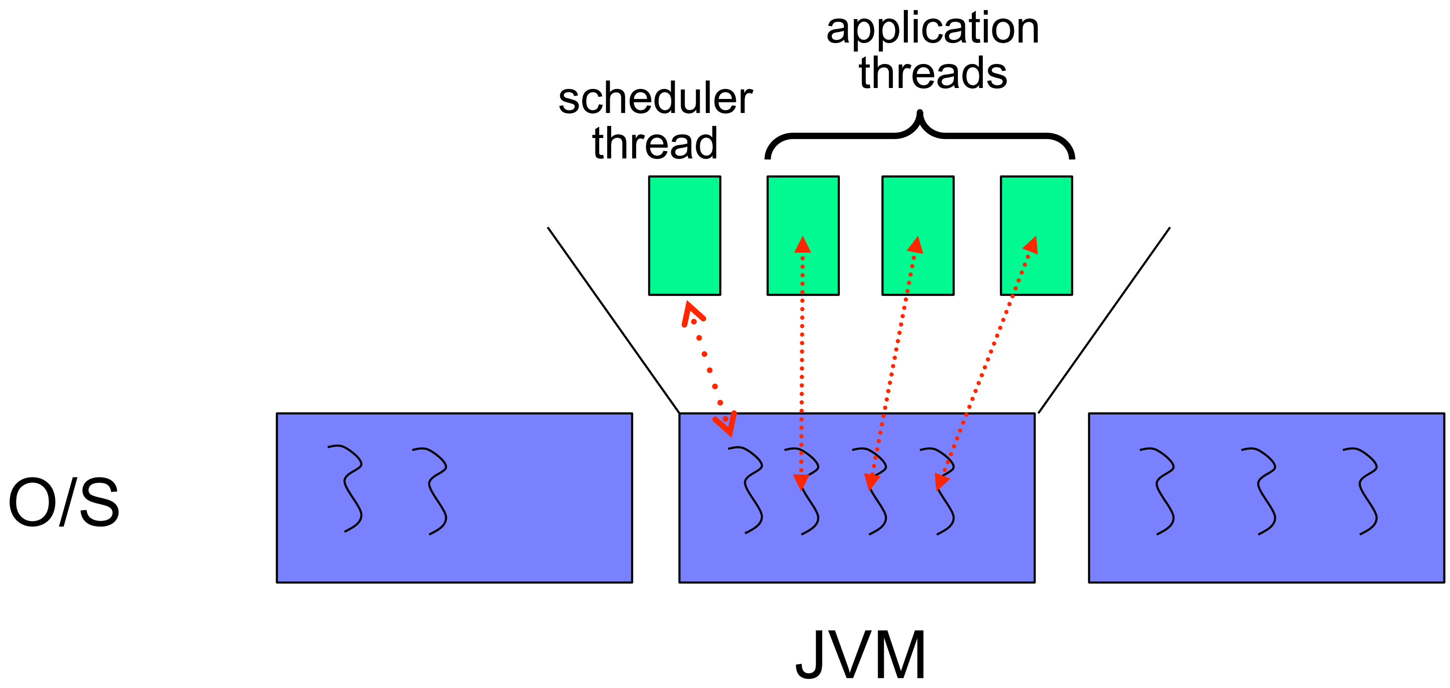


Beyond Green Threads

- Green threads have all the disadvantages of user-level threads (see earlier)
  - Most importantly: Cannot exploit multi-core, multi-processor architectures
- The JVM now provides native threads
  - Green threads are typically not available anymore
  - you can try to use “java -green” and see what your system says

Java Threads / Kernel Threads

- In modern JVMs, application threads are *mapped* to kernel threads



Threading Issues

- Semantics of **fork()** and **exec()** system calls
- Signal handling
  - Synchronous and asynchronous
- Thread cancellation of target thread
  - Asynchronous or deferred
- Thread-local storage
- Scheduler Activations

Semantics of fork() and exec()

- What happens when a thread calls fork()?
- Two possibilities:
  - A new process is created that has only one thread (the copy of the thread that called fork()), or
  - A new process is created with all threads of the original process (a copy of all the threads, including the one that called fork())
- Some OSes provide both options
  - In Linux the first option above is used
- If one calls exec() after fork(), all threads are “wiped out” anyway

Signals

- We've talked about signals for processes
  - Signal handlers are either default or user-specified
  - signal() and kill() are the system calls
- In a multi-threaded program, what happens?
- Multiple options
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the process
  - Deliver the signal to certain threads in the process
  - Assign a specific thread to receive all signals

Signals

- Most UNIX versions: a thread can say which signals it accepts and which signals it doesn't accept
- On Linux: dealing with threads and signals is tricky but well understood with many tutorials on the matter and man pages
  - man pthread_sigmask
  - man sigemptyset
  - man sigaction

Safe Thread Cancellation

- One potentially useful feature would be for a thread to simply terminate another thread
- Two possible approaches:
  - Asynchronous cancellation
    - One thread terminates another immediately
  - Deferred cancellation
    - A thread periodically checks whether it should terminate

Safe Thread Cancellation

- Two possible approaches:
  - Asynchronous cancellation
    - One thread terminates another immediately
  - Deferred cancellation
    - A thread periodically checks whether it should terminate

- Pthread code to create and cancel a thread:

```
pthread_t tid;

/* create the thread */
pthread_create(&tid, 0, worker, NULL);

 . . .

/* cancel the thread */
pthread_cancel(tid);

/* wait for the thread to terminate */
pthread_join(tid,NULL);
```

Safe Thread Cancellation

- Invoking thread cancellation requests cancellation, but actual cancellation depends on thread state

Mode	State	Type
Off	Disabled	–
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous

- If thread has cancellation disabled (**off**), cancellation remains pending until thread enables it
- Default type is deferred
  - Cancellation only occurs when thread reaches **cancellation point**
    - I.e. `pthread_testcancel()`
    - Then **cleanup handler** is invoked
- On Linux systems, thread cancellation is handled through signals

Safe Thread Cancellation

- The problem with asynchronous cancellation:
  - may lead to an inconsistent state or to a synchronization problem if the thread was in the middle of "something important"
  - Absolutely terrible bugs lurking in the shadows
- The problem with deferred cancellation: the code is cumbersome due to multiple cancellation points
  - should I die? should I die? should I die?
- In Java, the Thread.stop() method is deprecated, and so cancellation has to be deferred

Operating System Examples

- Windows Threads
- Linux Threads

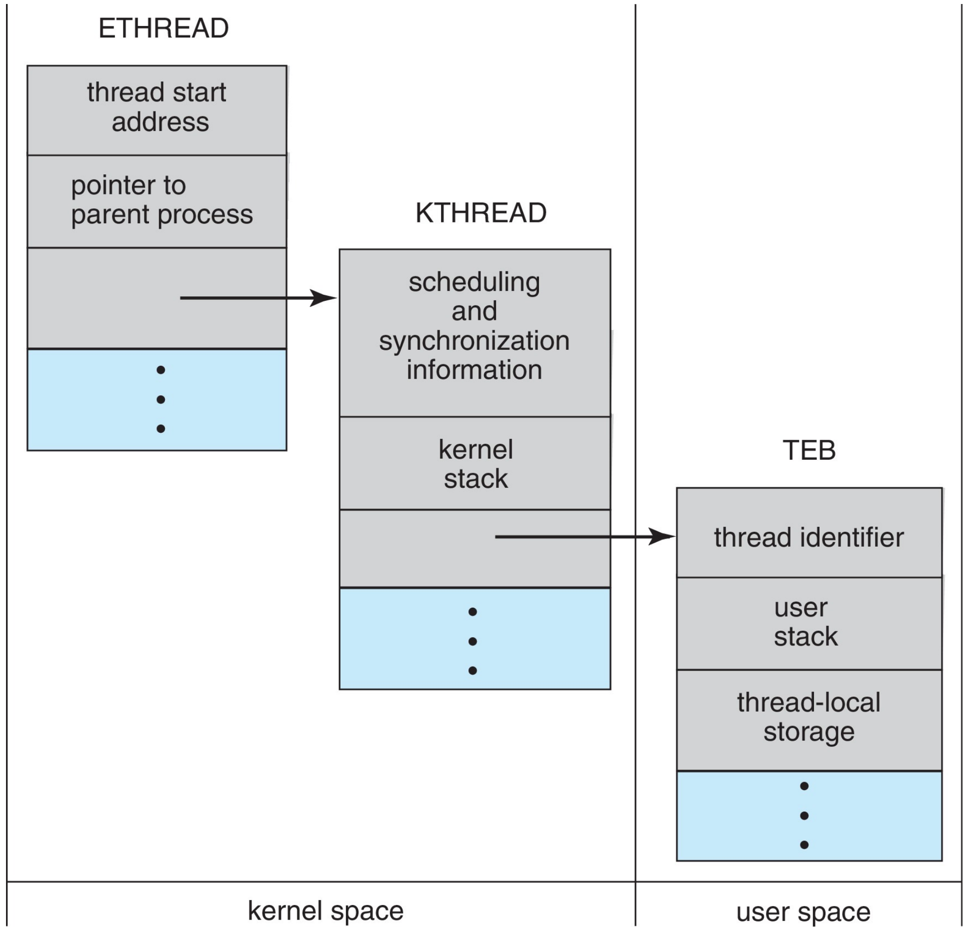
Windows Threads

- Windows API – primary API for Windows applications
- Implements the one-to-one mapping, kernel-level
- Each thread contains
  - A thread id
  - Register set representing state of processor
  - Separate user and kernel stacks for when thread runs in user mode or kernel mode
  - Private data storage area used by run-time libraries and dynamic link libraries (DLLs)
- The register set, stacks, and private storage area are known as the **context** of the thread

Windows Threads (Cont.)

- The primary data structures of a thread include:
  - ETHREAD (executive thread block) – includes pointer to process to which thread belongs and to KTHREAD, in kernel space
  - KTHREAD (kernel thread block) – scheduling and synchronization info, kernel-mode stack, pointer to TEB, in kernel space
  - TEB (thread environment block) – thread id, user-mode stack, thread-local storage, in user space

Windows Threads Data Structures



Linux Threads

- In Linux, a thread is also called a light-weight process (LWP)
- The clone() syscall is used to create a thread or a process
  - Shares execution context with its parent
  - pthread library uses clone() to implement threads. Refer to ./nptl/sysdeps/pthread/createthread.c

flag	meaning
CLONE_FS	File-system information is shared.
CLONE_VM	The same memory space is shared.
CLONE_SIGHAND	Signal handlers are shared.
CLONE_FILES	The set of open files is shared.

Linux Threads

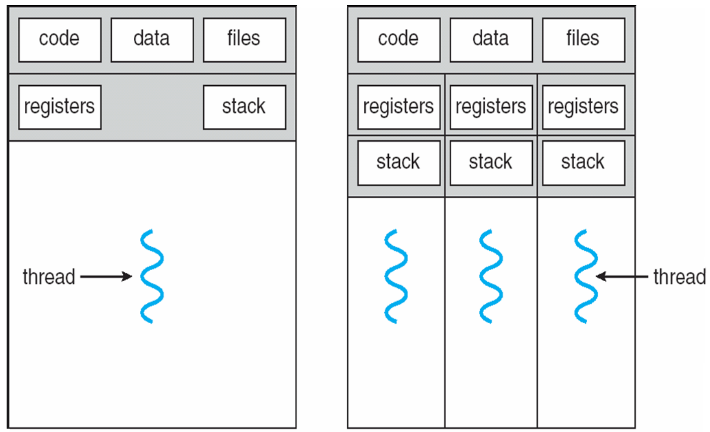
- Linux does not distinguish between PCB and TCB
  - Kernel data structure: task_struct

```
struct task_struct {
#ifdef CONFIG_THREAD_INFO_IN_TASK
        /*
         * For reasons of header soup (see current_thread_info()), this
         * must be the first element of task_struct.
         */
        struct thread_info              thread_info;
#endif
        /* -1 unrunnable, 0 runnable, >0 stopped: */
        volatile long                   state;

        /*
         * This begins the randomizable portion of task_struct. Only
         * scheduling-critical items should be added above here.
         */
        randomized_struct_fields_start

        void                            *stack;
        atomic_t                        usage;
        /* Per task flags (PF_*), defined further below: */
        unsigned int                    flags;
        unsigned int                    ptrace;
```

Linux Threads

- Single-threaded process vs multi-threaded process

```
wenbo@wenbo-desktop:~/KERNEL/linux.git$ ps -eLf
UID          PID  PPID   LWP  C NLWP STIME TTY          TIME CMD
root           1     0     1  0    1 3月11 ?        00:00:19 /sbin/init splash
root           2     0     2  0    1 3月11 ?        00:00:00 [kthreadd]
root           4     2     4  0    1 3月11 ?        00:00:00 [kworker/0:0H]
root           6     2     6  0    1 3月11 ?        00:00:00 [mm_percpu_wq]
root           7     2     7  0    1 3月11 ?        00:00:00 [ksoftirqd/0]
root           8     2     8  0    1 3月11 ?        00:00:31 [rcu_sched]
root           9     2     9  0    1 3月11 ?        00:00:00 [rcu_bh]
root          10     2    10  0    1 3月11 ?        00:00:00 [migration/0]
root          11     2    11  0    1 3月11 ?        00:00:00 [watchdog/0]

root         704     1   704  0    1 3月11 ?        00:00:00 /usr/sbin/cron -f
root         718     1   718  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   882  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   883  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   884  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   885  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   917  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   921  0   16 3月11 ?        00:00:01 /usr/lib/snapd/snapd
root         718     1   922  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   923  0   16 3月11 ?        00:00:01 /usr/lib/snapd/snapd
root         718     1   924  0   16 3月11 ?        00:00:01 /usr/lib/snapd/snapd
```



single-threaded process   multithreaded process

Linux Threads

- Single-threaded process vs multi-threaded process

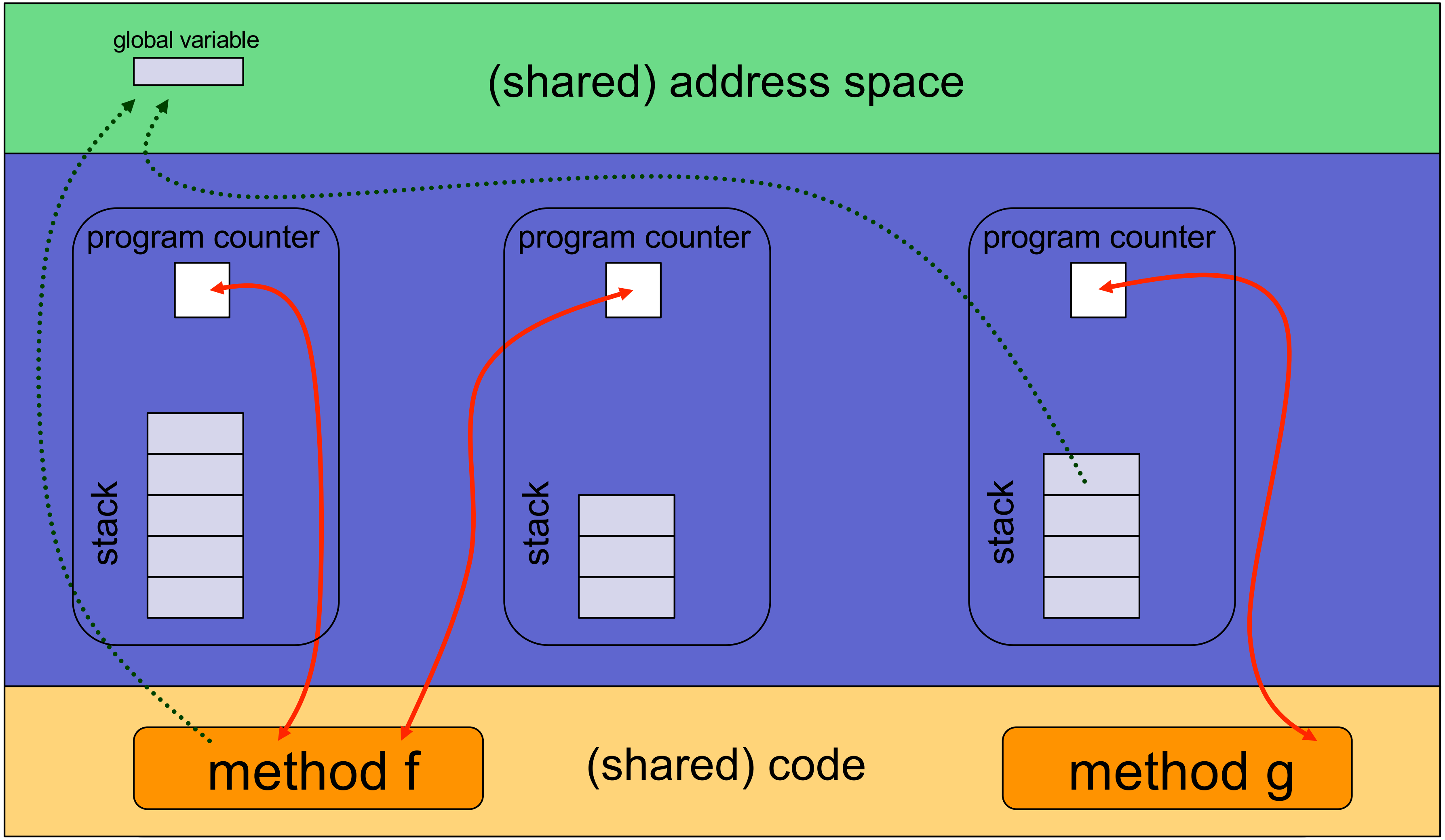
```
wenbo@wenbo-desktop:~/KERNEL/linux.git$ ps -eLf
UID          PID  PPID   LWP  C NLWP STIME TTY          TIME CMD
root           1     0     1  0    1 3月11 ?        00:00:19 /sbin/init splash
root           2     0     2  0    1 3月11 ?        00:00:00 [kthreadd]
root           4     2     4  0    1 3月11 ?        00:00:00 [kworker/0:0H]
root           6     2     6  0    1 3月11 ?        00:00:00 [mm_percpu_wq]
root           7     2     7  0    1 3月11 ?        00:00:00 [ksoftirqd/0]
root           8     2     8  0    1 3月11 ?        00:00:31 [rcu_sched]
root           9     2     9  0    1 3月11 ?        00:00:00 [rcu_bh]
root          10     2    10  0    1 3月11 ?        00:00:00 [migration/0]
root          11     2    11  0    1 3月11 ?        00:00:00 [watchdog/0]

root         704     1   704  0    1 3月11 ?        00:00:00 /usr/sbin/cron -f
root         718     1   718  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   882  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   883  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   884  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   885  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   917  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   921  0   16 3月11 ?        00:00:01 /usr/lib/snapd/snapd
root         718     1   922  0   16 3月11 ?        00:00:00 /usr/lib/snapd/snapd
root         718     1   923  0   16 3月11 ?        00:00:01 /usr/lib/snapd/snapd
root         718     1   924  0   16 3月11 ?        00:00:01 /usr/lib/snapd/snapd
```

```
        /* PID/PID hash table linkage. */
        struct pid                      *thread_pid;
        struct hlist_node               pid_links[PIDTYP
        struct list_head                thread_group;
        struct list_head                thread_node;

        struct completion               *vfork_done;

        /* CLONE_CHILD_SETTID: */
        int __user                      *set_child_tid;
```

Linux Threads

- Linux uses the same task_struct for ~~process and~~ thread
- A process is
  - either a single thread + an address space
    - PID is thread ID
  - or multiple threads + an address space
    - PID is the leading thread ID

Threads within Process



Threads with Process – What is shared

```
static void traversal_thread_group(struct task_struct * tsk){
        struct task_struct * curr_thread = NULL;
        unsigned long tg_offset = offsetof(struct task_struct, thread_group);

        curr_thread = (struct task_struct *) (((unsigned long)tsk->thread_group.next) - tg_offset);
        while (curr_thread != tsk){
                printk("\t\tTHREAD TSK=%llx\tPID=%d\tSTACK=%llx \tCOMM=%s\tMM=%llx\tACTIVE_MM=%llx\n",
                                (u64)curr_thread, curr_thread->pid, (u64)curr_thread->stack,
                                curr_thread->comm, (u64)curr_thread->mm, (u64)curr_thread->active_mm);
                curr_thread = (struct task_struct *) (((unsigned long)curr_thread->thread_group.next) - tg_offset);
        }
}

static void traversal_process(void) {
        struct task_struct * tsk = NULL;

        traversal_thread_group(&init_task);
        for_each_process(tsk){
                printk("PROCESS\tTHREAD TSK=%llx\tPID=%d\tSTACK=%llx \tCOMM=%s\tMM=%llx\tACTIVE_MM=%llx\n",
                                (u64)tsk, tsk->pid, (u64)tsk->stack, tsk->comm,
                                (u64)tsk->mm, (u64)tsk->active_mm);
                traversal_thread_group(tsk);
        }
}
```

Threads with Process – What is shared

```c
static void traversal_thread_group(struct task_struct * tsk){
        struct task_struct * curr_thread = NULL;
        unsigned long tg_offset = offsetof(struct task_struct, thread_group);

        curr_thread = (struct task_struct *) (((unsigned long)tsk->thread_group.next) - tg_offset);
        while (curr_thread != tsk){
                printk("\t\tTHREAD TSK=%llx\tPID=%d\tSTACK=%llx \tCOMM=%s\tMM=%llx\tACTIVE_MM=%llx\n",
                                (u64)curr_thread, curr_thread->pid, (u64)curr_thread->stack,
                                curr_thread->comm, (u64)curr_thread->mm, (u64)curr_thread->active_mm);
                curr_thread = (struct task_struct *) (((unsigned long)curr_thread->thread_group.next) - tg_offset);
        }
}

static void traversal_process(void) {
        struct task_struct * tsk = NULL;

        traversal_thread_group(&init_task);
        for_each_process(tsk){
                printk("PROCESS\tTHREAD TSK=%llx\tPID=%d\tSTACK=%llx \tCOMM=%s\tMM=%llx\tACTIVE_MM=%llx\n",
                                (u64)tsk, tsk->pid, (u64)tsk->stack, tsk->comm,
                                (u64)tsk->mm, (u64)tsk->active_mm);
                traversal_thread_group(tsk);
        }
}
```

```
PROCESS  THREAD TSK=ffff8c4c4bf3c5c0   PID=718 STACK=ffff985c82268000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46d52e80   PID=882 STACK=ffff985c82390000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46d545c0   PID=883 STACK=ffff985c822e8000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c491b45c0   PID=884 STACK=ffff985c8218c000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4beb1740   PID=885 STACK=ffff985c821ec000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4ae1ae80   PID=917 STACK=ffff985c823c8000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b562e80   PID=921 STACK=ffff985c82418000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c48340000   PID=922 STACK=ffff985c823b0000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c472bae80   PID=923 STACK=ffff985c821f4000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b5945c0   PID=924 STACK=ffff985c81fa8000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46775d00   PID=925 STACK=ffff985c822a8000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b692e80   PID=973 STACK=ffff985c82438000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b78ae80   PID=974 STACK=ffff985c823c0000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46e1dd00   PID=975 STACK=ffff985c824b8000  COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
```

Threads within Process – What is shared

```
PROCESS  THREAD TSK=ffff8c4c4bf3c5c0  PID=718 STACK=ffff985c82268000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46d52e80  PID=882 STACK=ffff985c82390000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46d545c0  PID=883 STACK=ffff985c822e8000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c491b45c0  PID=884 STACK=ffff985c8218c000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4beb1740  PID=885 STACK=ffff985c821ec000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4ae1ae80  PID=917 STACK=ffff985c823c8000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b562e80  PID=921 STACK=ffff985c82418000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c48340000  PID=922 STACK=ffff985c823b0000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c472bae80  PID=923 STACK=ffff985c821f4000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b5945c0  PID=924 STACK=ffff985c81fa8000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46775d00  PID=925 STACK=ffff985c822a8000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b692e80  PID=973 STACK=ffff985c82438000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c4b78ae80  PID=974 STACK=ffff985c823c0000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
         THREAD TSK=ffff8c4c46e1dd00  PID=975 STACK=ffff985c824b8000 COMM=snapd  MM=ffff8c4c46400840  ACTIVE_MM=ffff8c4c46400840
```

task_struct pid stack comm

mm_struct

Not Shared

Shared

User thread to kernel thread mapping

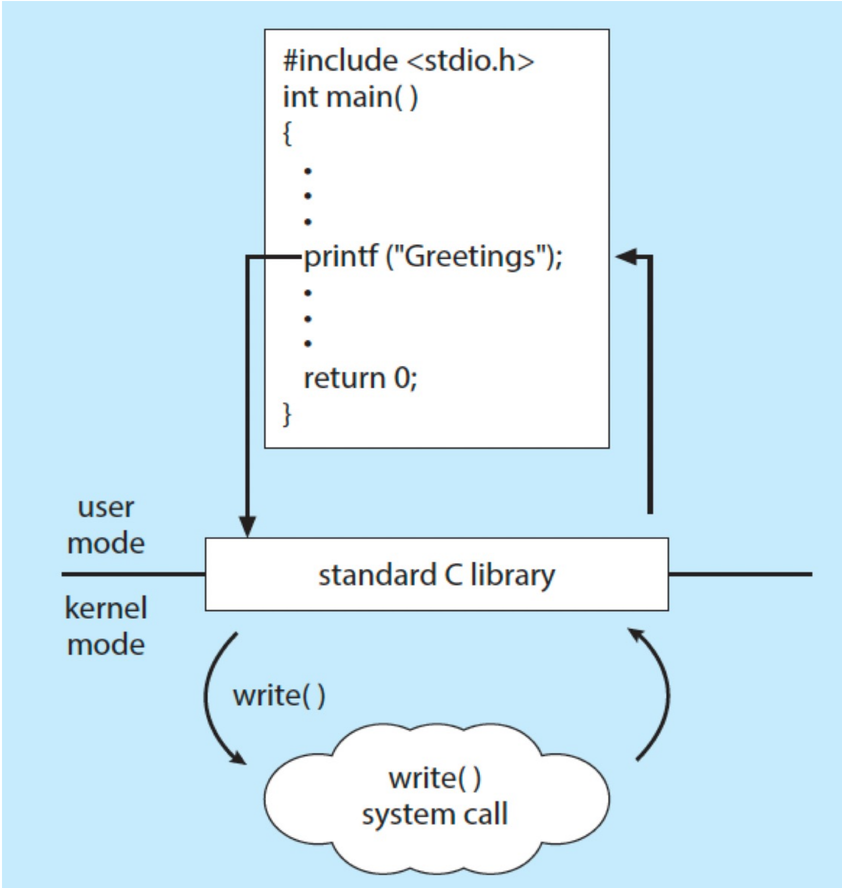
- One task in Linux
  - Same task_struct (PCB) means same thread
    - Also viewed as 1:1 mapping
    - One user thread maps to one kernel thread
    - But actually, they are the same thread
  - Can be executed in user space
    - User code, user space stack
  - Can be executed in kernel space
    - Kernel code, kernel space stack

User thread to kernel thread mapping

- One task
  - Can be a single-threaded process
    - One task_struct – PCB
    - PID is thread ID
  - Can be a multi-threaded process
    - Multiple task_struct
    - What is the PID?
  - Can be executed in user space
    - User code, user space stack
  - Can be executed in kernel space
    - Such as calls a system call
    - Execution flow traps to kernel
    - Execute kernel code, use kernel space stack

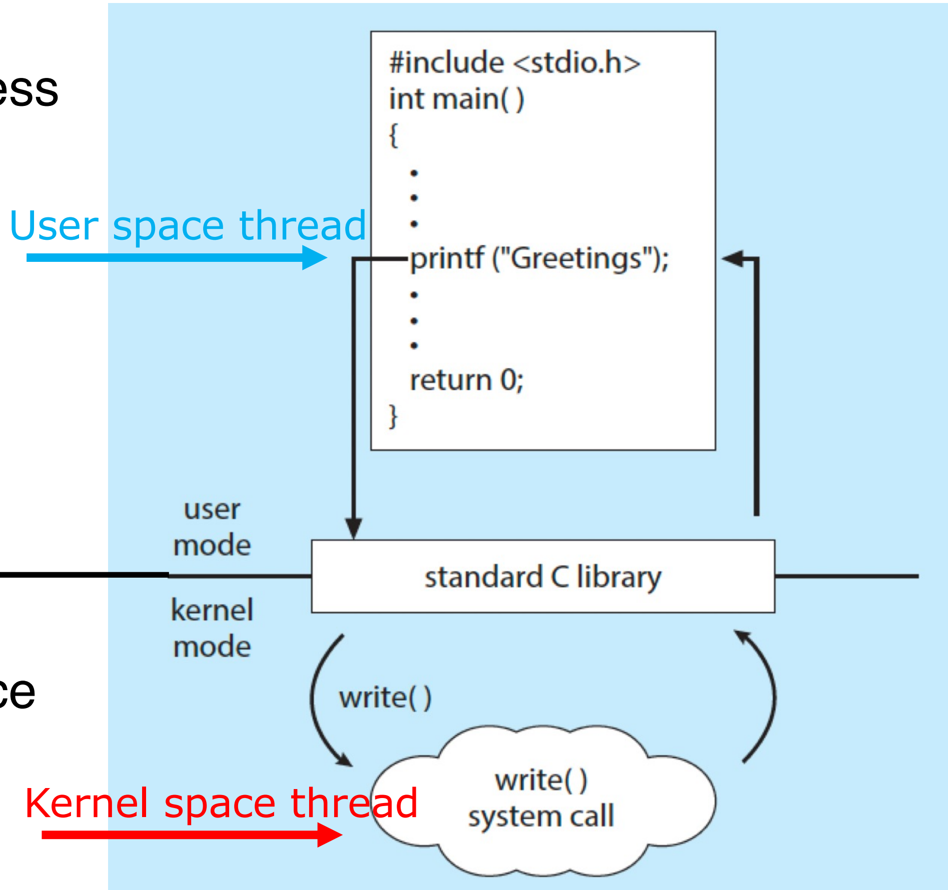
User thread to kernel thread mapping

- One task
  - Can be a single-threaded process
    - One task_struct – PCB
  - Can be a multi-threaded process
    - Multiple task_struct
  - Execution
    - Can be executed in user space
      - User code, user space stack
    - Can be executed in kernel space
      - Such as calls a system call
      - Execution flow traps to kernel
      - Execute kernel code, use kernel space stack



User thread to kernel thread mapping

- One task
  - Can be a single-threaded process
    - One task_struct – PCB
  - Can be a multi-threaded process
    - Multiple task_struct
  - Can be executed in user space
    - User code, user space stack



  - Can be executed in kernel space
    - Such as calls a system call
    - Execution flow traps to kernel
    - Execute kernel code, use kernel space stack

Takeaway

- Thread is the basic execution unit
  - Has its own registers, pc, stack
- Thread vs Process
  - What is shared and what is not
- Pros and cons of thread