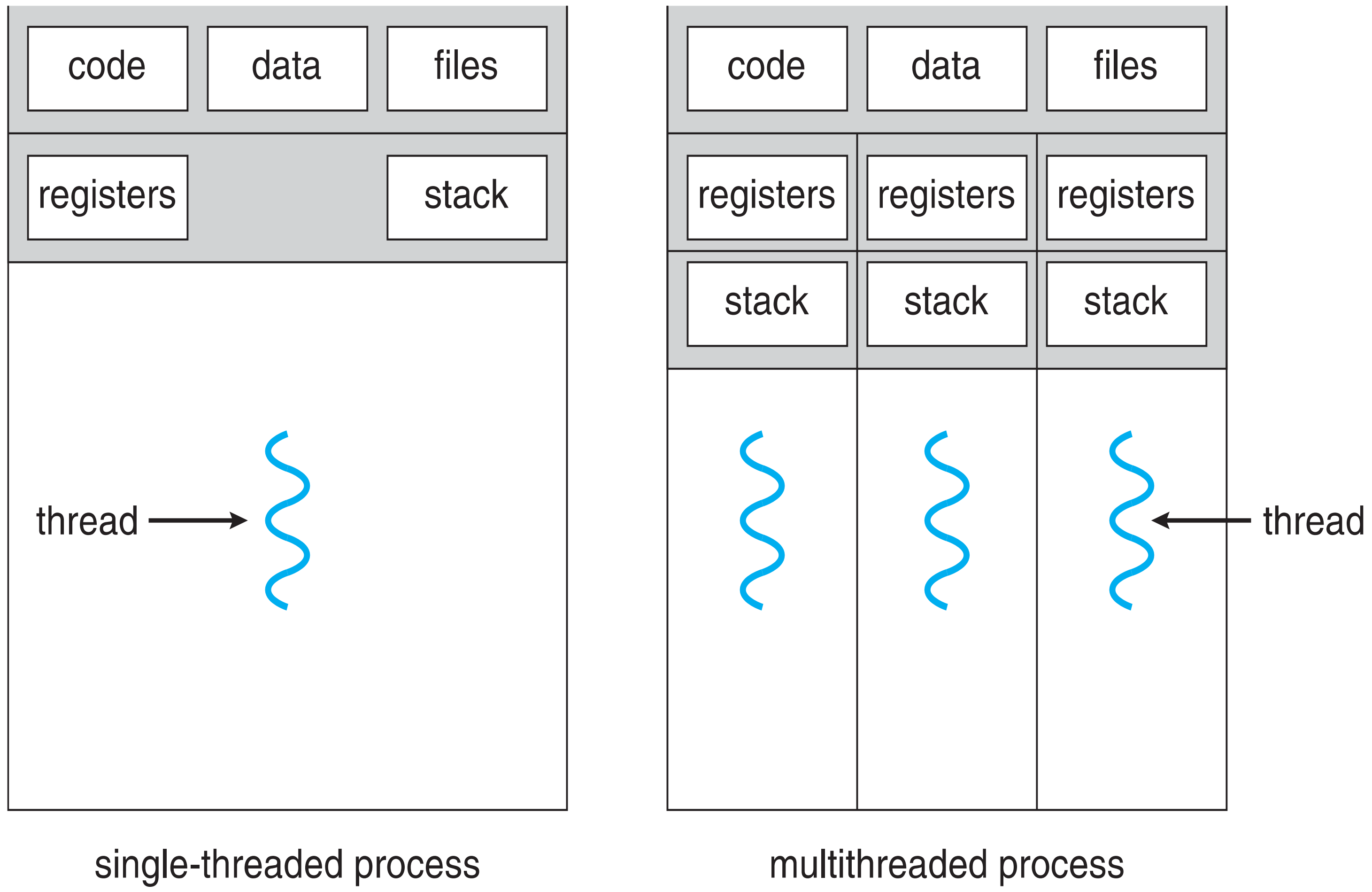
Threads

Threads

- A thread is a basic unit of CPU utilization;
- It comprises a thread ID, a program counter (PC), a register set, and a stack.
- It shares with other threads belonging to the same process its code section, data section, and other operating-system resources, such as open files and signals

```c
#include<stdio.h>
int main()
{
   while(1)
   {
      printf("Hello...\n");
   }
   return 0;
}
```

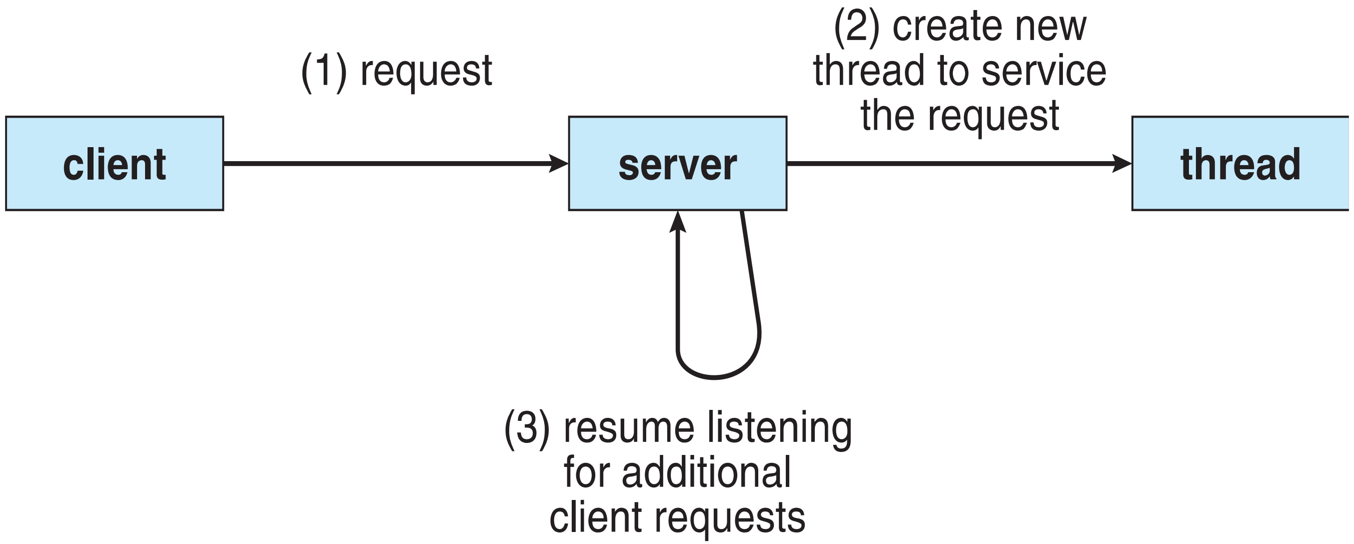
Check the entry in process list...


code
data
files
registers
stack
thread
code
data
files
registers
registers
registers
stack
stack
stack
thread
single-threaded process
multithreaded process

Examples

- **Web browser** might have one thread **display images or text** while another thread **retrieves data** from the network.
- A **word processor** may have a thread for **displaying graphics**, another

thread for **responding to keystrokes** from the user, and a third thread for performing **spelling and grammar checking** in the background



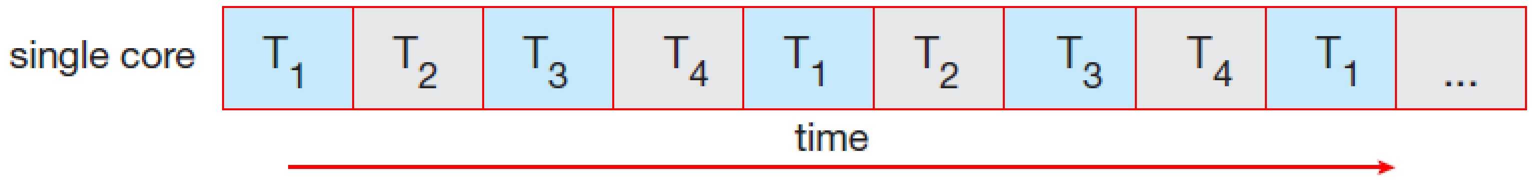
1. **Responsiveness**. Multithreading an interactive application may allow a program to continue running even if part of it is blocked or is performing a lengthy operation, thereby increasing responsiveness to the user. This quality is especially useful in designing user interfaces. For instance, consider what happens when a user clicks a button that results in the performance of a time-consuming operation. A single-threaded application would be unresponsive to the user until the operation had been completed. In contrast, if the time-consuming operation is performed in a separate, asynchronous thread, the application remains responsive to the user.

2. **Resource sharing.** Processes can share resources only through techniques such as shared memory and message passing. Such techniques must be explicitly arranged by the programmer. However, threads share the memory and the resources of the process to which they belong by default. The benefit of sharing code and data is that it allows an application to have several different threads of activity within the same address space.

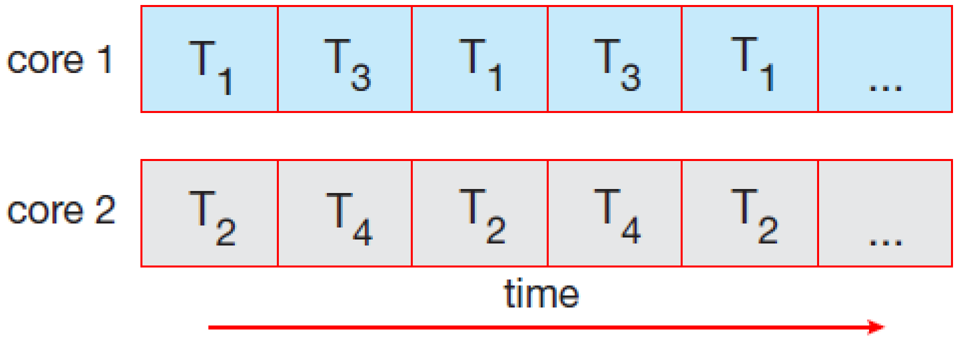
3. **Economy**. Allocating memory and resources for process creation is costly. Because threads share the resources of the process to which they belong, it is more economical to create and context-switch threads. Empirically gauging the difference in overhead can be difficult, but in general thread creation consumes less time and memory than process creation. Additionally, context switching is typically faster between threads than between processes.

4. **Scalability.** The benefits of multithreading can be even greater in a multiprocessor architecture, where threads may be running in parallel on different processing cores. A single-threaded process can run on only one processor, regardless how many are available. We explore this issue further in the following section.

Multicore Programming



Concurrent execution on a single-core system.

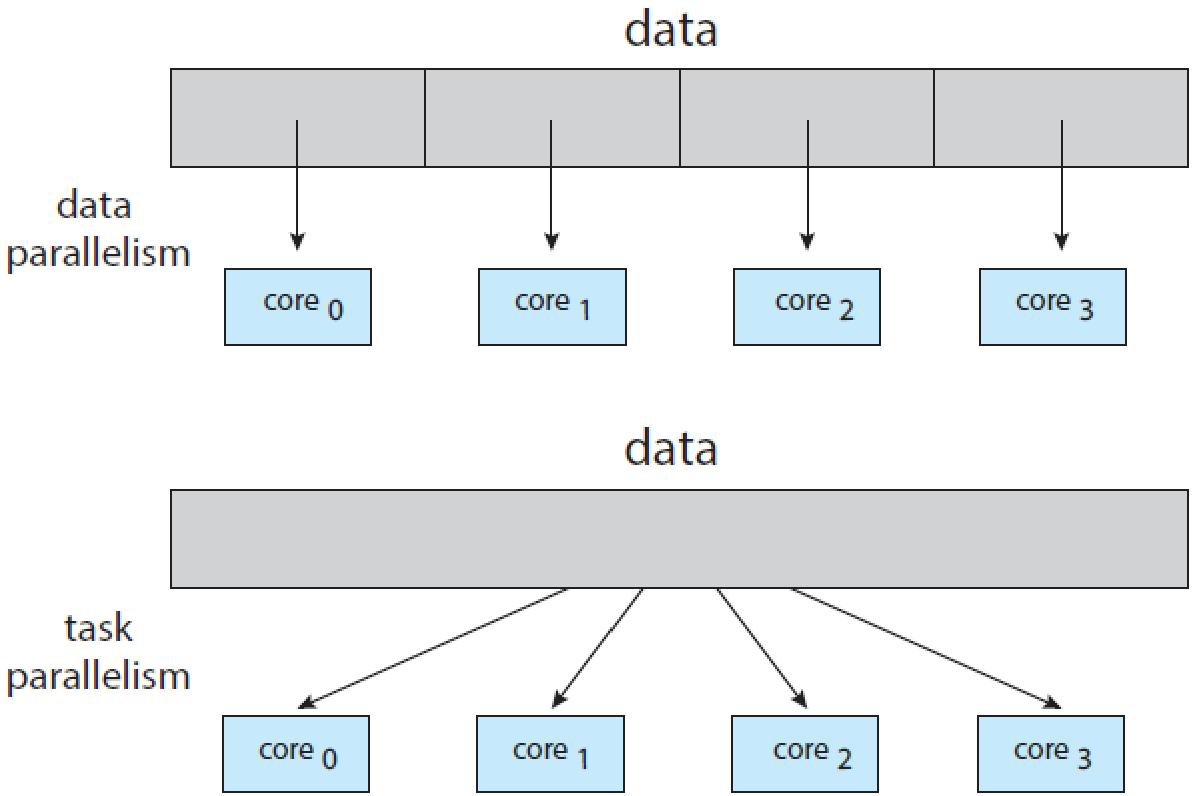


Parallel execution on a multicore system.

Types of Parallelism

In general, there are two types of parallelism: data parallelism and task parallelism. **Data parallelism** focuses on distributing subsets of the same data across multiple computing cores and performing the same operation on each core. Consider, for example, summing the contents of an array of size N. On a single-core system, one thread would simply sum the elements $[0] \ldots [N-1]$. On a dual-core system, however, thread A, running on core 0, could sum the elements $[0] \ldots [N/2-1]$ while thread B, running on core 1, could sum the elements $[N/2] \ldots [N-1]$. The two threads would be running in parallel on separate computing cores.

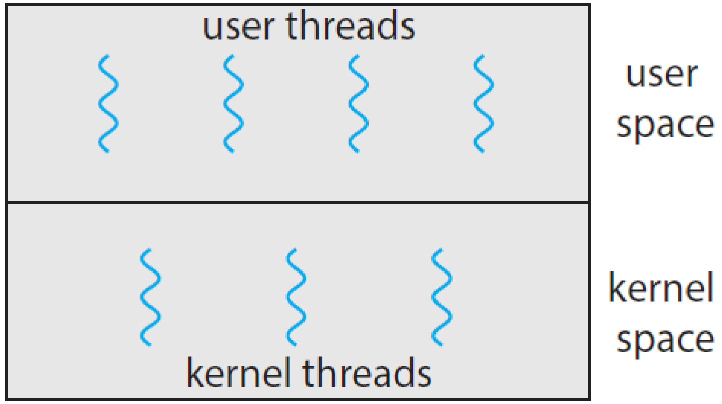
Task parallelism involves distributing not data but tasks (threads) across multiple computing cores. Each thread is performing a unique operation. Different threads may be operating on the same data, or they may be operating on different data. Consider again our example above. In contrast to that situation, an example of task parallelism might involve two threads, each performing a unique statistical operation on the array of elements. The threads again are operating in parallel on separate computing cores, but each is performing a unique operation.



data
data
parallelism
core 0
core 1
core 2
core 3
data
task
parallelism
core 0
core 1
core 2
core 3

User level vs Kernel level threads

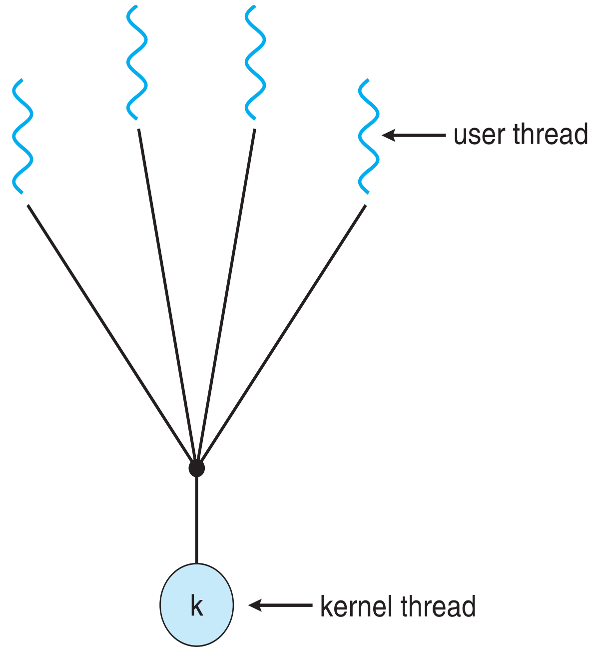
- **User threads** - management done by user-level threads library
- Three primary thread libraries:
  - POSIX **Pthreads**
  - Windows threads
  - Java threads
- **Kernel threads** - Supported by the Kernel
- Examples – virtually all general purpose operating systems, including:
  - Windows
  - Solaris
  - Linux
  - Tru64 UNIX
  - Mac OS X



- Many-to-One
- One-to-One
- Many-to-Many

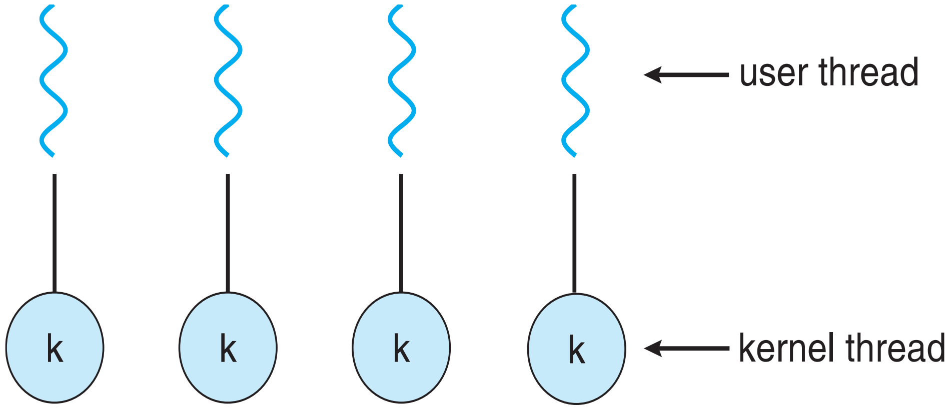
Many-to-One

- **Many user-level threads** mapped to **single kernel thread**
- One thread blocking causes all to block
- Multiple threads may not run in parallel on muticore system because only one may be in kernel at a time
- Few systems currently use this model
- Examples:
    - Solaris Green Threads
    - GNU Portable Threads



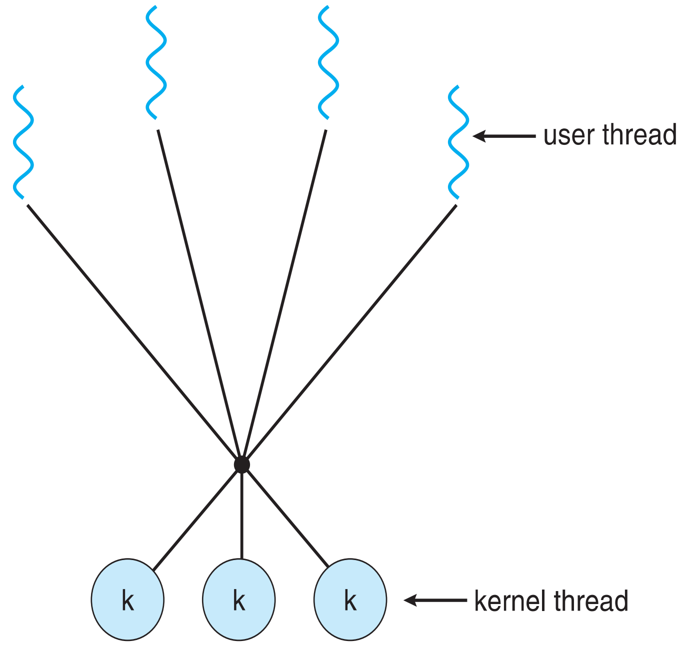
One-to-One

- **Each user-level thread** maps to kernel thread
- Creating a user-level thread creates a kernel thread
- **More concurrency** than many-to-one
- **Number of threads** per process sometimes **restricted** due to overhead
- Examples
  - Windows
  - Linux
  - Solaris 9 and later



Many-to-Many

- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9
- Windows with the *ThreadFiber* package



- **Thread library** provides programmer with API for creating and managing threads
- Two primary ways of implementing
  - Library entirely in user space
  - Kernel-level library supported by the OS
  - A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization

- Pthread Library (60+ functions)
  - Thread management: create, exit, detach, join, . .
  - Mutex locks: init, destroy, lock, unlock, . . .
  - Condition variables: init, destroy, wait, timed wait, ...
- Programs must include the file pthread.h
- Programs must be linked with the pthread library (**-lpthread**)

Types: **`pthread[_object]_t`**

Functions: **`pthread[_object]_action`**

Constants/Macros: **`PTHREAD_PURPOSE`**

Examples:

- pthread_t: the type of a thread
- pthread_create(): creates a thread
- pthread_mutex_t: the type of a mutex lock
- pthread_mutex_lock(): lock a mutex
- PTHREAD_CREATE_DETACHED

```c
#include<stdio.h>
int main()
{
  while(1)
  {
    printf("Hello...\n");
  }
  return 0;
}
```

Check the entry in process list...

GNU **Linux, Blue Gene**	`gcc -pthread`	GNU C
	`g++ -pthread`	GNU C++

pthread_create (thread,attr,start_routine,arg)

pthread_exit (status)

pthread_cancel (thread)

pthread_attr_init (attr)

pthread_attr_destroy (attr)

Creates a new thread

- `int pthread_create ( pthread_t *thread, pthread_attr_t *attr, void * (*start_routine) (void *), void *arg);`

- Returns 0 to indicate success, otherwise returns error code...
  - thread: output argument for the id of the new thread
  - attr: input argument that specifies the attributes of the thread to be created (NULL = default attributes)
  - start_routine: function to use as the start of the new thread must have prototype: void * foo(void*)
  - arg: argument to pass to the new thread routine. If the thread routine requires multiple arguments, they must be passed bundled up in an array or a structure

Terminates the calling thread

- void pthread_exit(void *retval);

- The return value is made available to another thread calling a pthread_join()
- The **return value** of the function serves as the argument to the (implicitly called) pthread_exit().

- **Causes the calling thread to wait for another thread to terminate**
- int pthread_join(pthread_t thread, void **value_ptr);

  - thread: input parameter, id of the thread to wait on
  - value_ptr: output parameter, value given to pthread_exit() by the terminating thread (which happens to always be a void *)

Returns 0 to indicate success, error code otherwise

Multiple simultaneous calls for the same thread are not allowed

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

int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* threads call this function */

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

  if (argc != 2) {
    fprintf(stderr,"usage: a.out <integer value>\n");
    return -1;
  }
  if (atoi(argv[1]) < 0) {
    fprintf(stderr,"%d must be >= 0\n",atoi(argv[1]));
    return -1;
  }
```

```
  /* get the default attributes */
  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);
}

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

  for (i = 1; i <= upper; i++)
    sum += i;

  pthread_exit(0);
}
```

```
#define NUM_THREADS 10

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

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

Example

```
#include<unistd.h>
#include<stdio.h>
#include<pthread.h>
int first()
{            pthread_self()
 int i;
 for(i=0;;i++)
 {
     printf("\nFirst: %d",i);
     sleep(1);
 }
}
```

```
int main()
{
    pthread_t th;
    int i;
    pthread_create(&th, 0,(void
                *)&first,NULL);
    for(i=0;;i++)
    {
        printf("\nMain: %d",i);
        sleep(1);
    }
    pthread_join(th, NULL);
    return 0;
}
```

Mutex lock

```
#include <pthread.h>

pthread_mutex_t mutex;

/* create and initialize the mutex lock */
pthread_mutex_init(&mutex,NULL);
```

```
/* acquire the mutex lock */
pthread_mutex_lock(&mutex);

/* critical section */

/* release the mutex lock */
pthread_mutex_unlock(&mutex);
```

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

int mails = 0;
pthread_mutex_t mutex;

void* routine() {
    for (int i = 0; i < 10000000; i++) {
        pthread_mutex_lock(&mutex);
        mails++;
        pthread_mutex_unlock(&mutex);
        // read mails
        // increment
        // write mails
    }
}
```

```c
int main(int argc, char* argv[]) {
    pthread_t p1, p2, p3, p4;
    pthread_mutex_init(&mutex, NULL);
    if (pthread_create(&p1, NULL, &routine, NULL) != 0) {
        return 1;
    }
    if (pthread_create(&p2, NULL, &routine, NULL) != 0) {
        return 2;
    }
    if (pthread_create(&p3, NULL, &routine, NULL) != 0) {
        return 3;
    }
    if (pthread_create(&p4, NULL, &routine, NULL) != 0) {
        return 4;
    }
    if (pthread_join(p1, NULL) != 0) {
        return 5;
    }
    if (pthread_join(p2, NULL) != 0) {
        return 6;
    }
    if (pthread_join(p3, NULL) != 0) {
        return 7;
    }
    if (pthread_join(p4, NULL) != 0) {
        return 8;
    }
    pthread_mutex_destroy(&mutex);
    printf("Number of mails: %d\n", mails);
    return 0;
}
```

Condition variables

- There are many cases where a **thread wishes to <u>check</u>** whether a **condition** is true before continuing its execution.
- Example:
  - A parent thread might wish to check whether a child thread has completed.
  - This is often called a `join()`.

A Parent Waiting For Its Child

```
void *child(void *arg) {
    printf("child\n");
    // XXX how to indicate we are done?
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    // XXX how to wait for child?
    printf("parent: end\n");
    return 0;
}
```

What we would like to see here is:

```
parent: begin
child
parent: end
```

```c
volatile int done = 0;

void *child(void *arg) {
    printf("child\n");
    done = 1;
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    while (done == 0)
        ; // spin
    printf("parent: end\n");
    return 0;
}
```

- This is hugely <u>inefficient</u> as the parent spins and **wastes CPU time**.

Condition variable

- **Waiting** on the condition
  - **An explicit queue** that threads can put themselves on when some state of execution is not as desired.
- **Signaling** on the condition
  - **Some other thread**, when it changes said state, can wake one of those waiting threads and allow them to continue.

- Declare condition variable

```
pthread cond t c;
```

  - Proper initialization is required.

```
pthread_mutex_t mutex;
pthread_cond_t cond_var;

pthread_mutex_init(&mutex,NULL);
pthread_cond_init(&cond_var,NULL);
```

- Operation (the POSIX calls)

```
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);     // wait()
pthread_cond_signal(pthread_cond_t *c);                        // signal()
```

  - The wait() call takes a mutex as a parameter.
    - The wait() call **release the lock** and put the calling thread to sleep.
    - When the thread wakes up, it must **re-acquire the lock**.

```
pthread_mutex_t mutex;
pthread_cond_t cond_var;

pthread_mutex_init(&mutex,NULL);
pthread_cond_init(&cond_var,NULL);
```

The `pthread_cond_wait()` function is used for waiting on a condition variable. The following code illustrates how a thread can wait for the condition `a == b` to become true using a Pthread condition variable:

```
pthread_mutex_lock(&mutex);
while (a != b)
     pthread_cond_wait(&cond_var, &mutex);

pthread_mutex_unlock(&mutex);
```

```
pthread_mutex_lock(&mutex);
a = b;
pthread_cond_signal(&cond_var);
pthread_mutex_unlock(&mutex);
```

```c
int done = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c = PTHREAD_COND_INITIALIZER;

void thr_exit() {
        Pthread_mutex_lock(&m);
        done = 1;
        Pthread_cond_signal(&c);
        Pthread_mutex_unlock(&m);
}

void *child(void *arg) {
        printf("child\n");
        thr_exit();
        return NULL;
}

void thr_join() {
        Pthread_mutex_lock(&m);
        while (done == 0)
                Pthread_cond_wait(&c, &m);
        Pthread_mutex_unlock(&m);
}
```

(cont.)

```
int main(int argc, char *argv[]) {
        printf("parent: begin\n");
        pthread_t p;
        Pthread_create(&p, NULL, child, NULL);
        thr_join();
        printf("parent: end\n");
        return 0;
}
```

- **Parent:**
  - Create the child thread and continues running itself.
  - Call into `thr_join()` to wait for the child thread to complete.
    - Acquire the lock
    - Check if the child is done
    - Put itself to sleep by calling `wait()`
    - Release the lock
- **Child:**
  - Print the message "child"
  - Call `thr_exit()` to wake the parent thread
    - Grab the lock
    - Set the state variable `done`
    - Signal the parent thus waking it.

```
void thr_exit() {
        done = 1;
        Pthread_cond_signal(&c);
}

void thr_join() {
        if (done == 0)
                Pthread_cond_wait(&c);
}
```

- The issue here is a subtle **race condition**.
  - The parent calls `thr_join()`.
    - The parent checks the value of `done`.
    - It will see that it is 0 and try to go to sleep.
    - Just before it calls wait to go to sleep, the parent is <u>interrupted</u> and the child runs.
  - The child changes the state variable `done` to 1 and signals.
    - But no thread is waiting and thus no thread is woken.
    - When the parent runs again, it sleeps forever.
- Always hold the lock while signaling

The importance of the state variable **done**

```
void thr_exit() {
        Pthread_mutex_lock(&m);
        Pthread_cond_signal(&c);
        Pthread_mutex_unlock(&m);
}

void thr_join() {
        Pthread_mutex_lock(&m);
        Pthread_cond_wait(&c, &m);
        Pthread_mutex_unlock(&m);
}
```

thr_exit() and thr_join() without variable done (it is a broken code)

- Imagine the case where the child runs immediately.
  - The child will signal, but there is no thread asleep on the condition.
  - When the parent runs, it will call wait and be stuck.
  - **No thread will ever wake it.**

```c
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <errno.h>

pthread_mutex_t mutexFuel;
pthread_cond_t condFuel;
int fuel = 0;

void* fuel_filling(void* arg) {
    for (int i = 0; i < 5; i++) {
        pthread_mutex_lock(&mutexFuel);
        fuel += 15;
        printf("Filled fuel... %d\n", fuel);
       pthread_cond_signal(&condFuel);
        pthread_mutex_unlock(&mutexFuel);
     sleep(1);
    }
}
```

```c
void* car(void* arg) {
    pthread_mutex_lock(&mutexFuel);
    while (fuel < 40) {
        printf("No fuel. Waiting...\n");
        pthread_cond_wait(&condFuel, &mutexFuel);
        // Equivalent to:
        // pthread_mutex_unlock(&mutexFuel);
        // wait for signal on condFuel
        // pthread_mutex_lock(&mutexFuel);
    }
    fuel -= 40;
    printf("Got fuel. Now left: %d\n", fuel);
    pthread_mutex_unlock(&mutexFuel);
}
```

```c
int main(int argc, char* argv[]) {
    pthread_t th[2];
    pthread_mutex_init(&mutexFuel, NULL);
    pthread_cond_init(&condFuel, NULL);
    for (int i = 0; i < 2; i++) {
        if (i == 1) {
            if (pthread_create(&th[i], NULL, &fuel_filling, NULL) != 0) {
                perror("Failed to create thread");
            }
        } else {
            if (pthread_create(&th[i], NULL, &car, NULL) != 0) {
                perror("Failed to create thread");
            }
        }
    }
    for (int i = 0; i < 2; i++) {
        if (pthread_join(th[i], NULL) != 0) {
            perror("Failed to join thread");
        }
    }
    pthread_mutex_destroy(&mutexFuel);
    pthread_cond_destroy(&condFuel);
    return 0;
}
```

Return values – with return statement

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

void* roll_dice() {
    int value = (rand() % 6) + 1;
    int* result = malloc(sizeof(int));
    *result = value;
    // printf("%d\n", value);
    printf("Thread result: %p\n", result);
    return (void*) result;
}
```

```
int main(int argc, char* argv[]) {
    int* res;
    srand(time(NULL));
    pthread_t th;
    if (pthread_create(&th, NULL, &roll_dice, NULL) != 0) {
        return 1;
    }
    if (pthread_join(th, (void**) &res) != 0) {
        return 2;
    }
    printf("Main res: %p\n", res);
    printf("Result: %d\n", *res);
    free(res);
    return 0;
}
```

Return values – with pthread_exit statement

```c
#include <stdlib.h>
#include <stdlib.h>
#include <stdio.h>
#include <pthread.h>
#include <time.h>

void* roll_dice() {
    int value = (rand() % 6) + 1;
    int* result = malloc(sizeof(int));
    *result = value;
    sleep(2);
    printf("Thread result: %d\n", value);
    pthread_exit((void*) result);
}
```

```c
int main(int argc, char* argv[]) {
    int* res;
    srand(time(NULL));
    pthread_t th;
    if (pthread_create(&th, NULL, &roll_dice, NULL) != 0) {
        return 1;
    }
    // pthread_exit(0);
    if (pthread_join(th, (void**) &res) != 0) {
        return 2;
    }
    printf("Result: %d\n", *res);
    free(res);
    return 0;
}
```

Return values – with pthread_exit statement

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

void* roll_dice() {
    int value = (rand() % 6) + 1;
    int* result = malloc(sizeof(int));
    *result = value;
    sleep(2);
    printf("Thread result: %d\n", value);
    pthread_exit((void*) result);
}
```

```
int main(int argc, char* argv[]) {
    int* res;
    srand(time(NULL));
    pthread_t th;
    if (pthread_create(&th, NULL, &roll_dice, NULL) != 0) {
        return 1;
    }
    // pthread_exit(0);
    if (pthread_join(th, (void**) &res) != 0) {
        return 2;
    }
    printf("Result: %d\n", *res);
    free(res);
    return 0;
}
```

Detach

```c
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <time.h>

#define THREAD_NUM 2

void* routine(void* args) {
    sleep(1);
    printf("Finished execution\n");
}
```

```c
int main(int argc, char *argv[]) {
    pthread_t th[THREAD_NUM];
    int i;
    for (i = 0; i < THREAD_NUM; i++) {
        if (pthread_create(&th[i], NULL, &routine, NULL) != 0) {
            perror("Failed to create thread");
        }
        pthread_detach(th[i]);
    }

    for (i = 0; i < THREAD_NUM; i++) {
        if (pthread_join(th[i], NULL) != 0) {
            perror("Failed to join thread");
        }
    }
    // pthread_exit(0);
}
```

Detach

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <time.h>

#define THREAD_NUM 2

void* routine(void* args) {
    sleep(1);
    printf("Finished execution\n");
}
```

```
int main(int argc, char *argv[]) {
    pthread_t th[THREAD_NUM];
    pthread_attr_t detachedThread;
    pthread_attr_init(&detachedThread);
    pthread_attr_setdetachstate(&detachedThread, PTHREAD_CREATE_DETACHE

    int i;
    for (i = 0; i < THREAD_NUM; i++) {
        if (pthread_create(&th[i], &detachedThread, &routine, NULL) != 0) {
            perror("Failed to create thread");
        }
        // pthread_detach(th[i]);
    }

    for (i = 0; i < THREAD_NUM; i++) {
        if (pthread_join(th[i], NULL) != 0) {
            perror("Failed to join thread");
        }
    }
    pthread_attr_destroy(&detachedThread);
    pthread_exit(0);
}
```

Barriers

```c
#include <stdio.h>
#include <pthread.h>
#include <unistd.h>  // For sleep()

#define NUM_THREADS 3  // Number of threads

pthread_barrier_t barrier;  // Declare the barrier

void* worker(void* arg) {
    int thread_id = *(int*)arg;
    printf("Thread %d is performing its task...\n", thread_id);

   printf("Thread %d reached the barrier and is waiting...\n", thread_id);

    // Wait until all threads reach the barrier
    pthread_barrier_wait(&barrier);

    printf("Thread %d passed the barrier and continues execution.\n", thread_id);

    return NULL;
}
```

```c
int main() {
    pthread_t threads[NUM_THREADS];
    int thread_ids[NUM_THREADS];

    // Initialize the barrier for NUM_THREADS threads
    pthread_barrier_init(&barrier, NULL, NUM_THREADS);

    // Create threads
    for (int i = 0; i < NUM_THREADS; i++) {
        thread_ids[i] = i + 1;
        pthread_create(&threads[i], NULL, worker, &thread_ids[i]);
    }
    // Wait for all threads to complete
    for (int i = 0; i < NUM_THREADS; i++) {
        pthread_join(threads[i], NULL);
    }
    // Destroy the barrier
    pthread_barrier_destroy(&barrier);
    printf("All threads have completed execution.\n");
    return 0;
}
```