Operating Systems

Prof. Yongkun Li
中国科大-计算机学院 教授
http://staff.ustc.edu.cn/~ykli

Ch4 Threads

Chapter 4: Threads

- Thread Concepts
  - Why use threads
  - Structure in Memory
  - Benefits and Challenges
  - Thread Models
- Programming
  - Basic Programming: Pthreads Library
  - Implicit Threading: Thread Pools & OpenMP

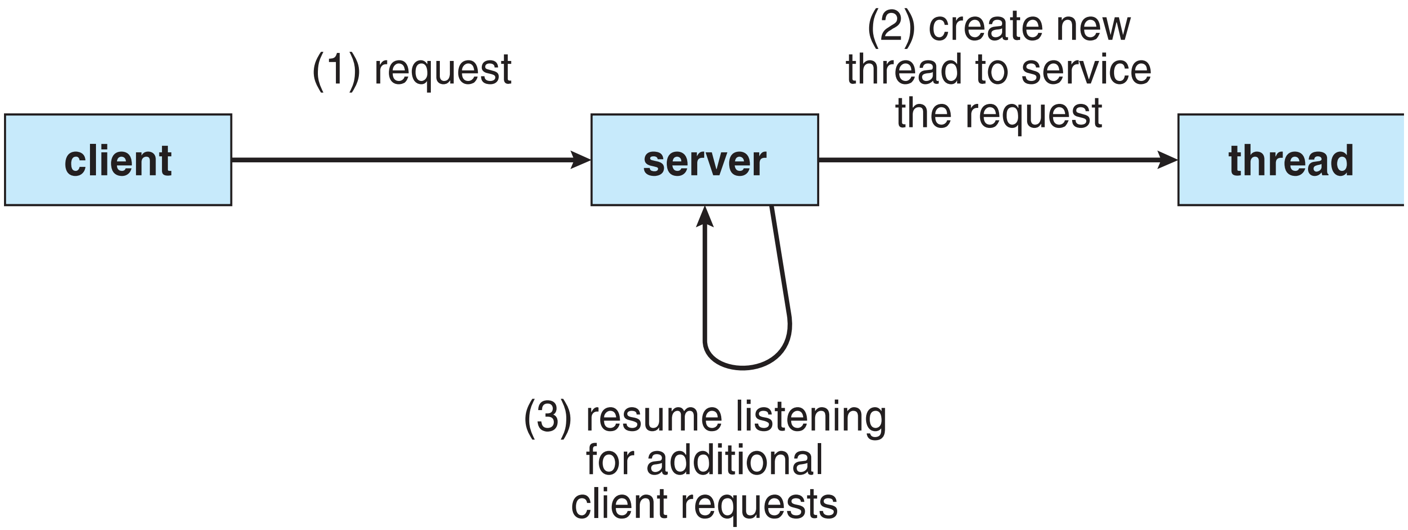
Multi-threading
- Motivation

Motivation - Application Side

- Most software applications are multithreaded, each application is implemented as a process with several threads of control
  - Web browser
    - displays images, retrieve data from network
  - Word processor
    - display graphics, respond to keystrokes, spelling & grammar checking

Motivation - Application Side

- Most software applications are multithreaded
  - Web browser
  - Word processor
  - Similar tasks in a single application (web server)
    - Accept client requests, service the requests
    - Usually serve thousands of clients



Motivation – Application Side

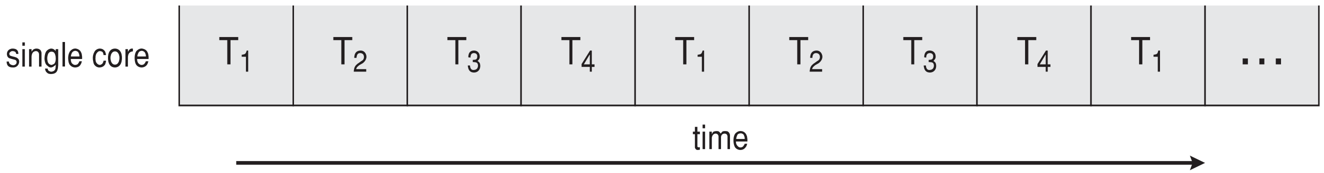
- Why not create a process for each task?
  - Process creation is
    - Heavy-weighted
    - Resource intensive
- Still remember what kinds of data are included in a process…
  - Text, data, stack, heap in user-space memory
  - PCB in kernel-space memory
- Many of the data can be shared between multiple tasks within an application

Motivation – System Side

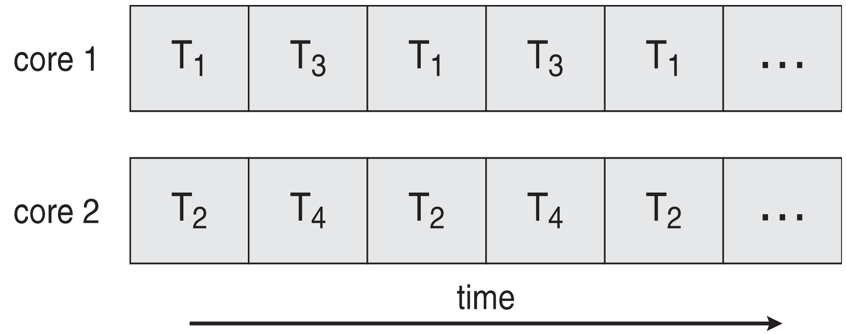
- Modern computers usually contain multicores
  - But, each processor can run only one process at a time
  - CPU is not fully utilized
- How to improve the efficiency?
  - Assign one task to each core
  - Real parallelism (not just concurrency with interleaving on single-core system)

Concurrency vs. Parallelism

Concurrent execution on single-core system:



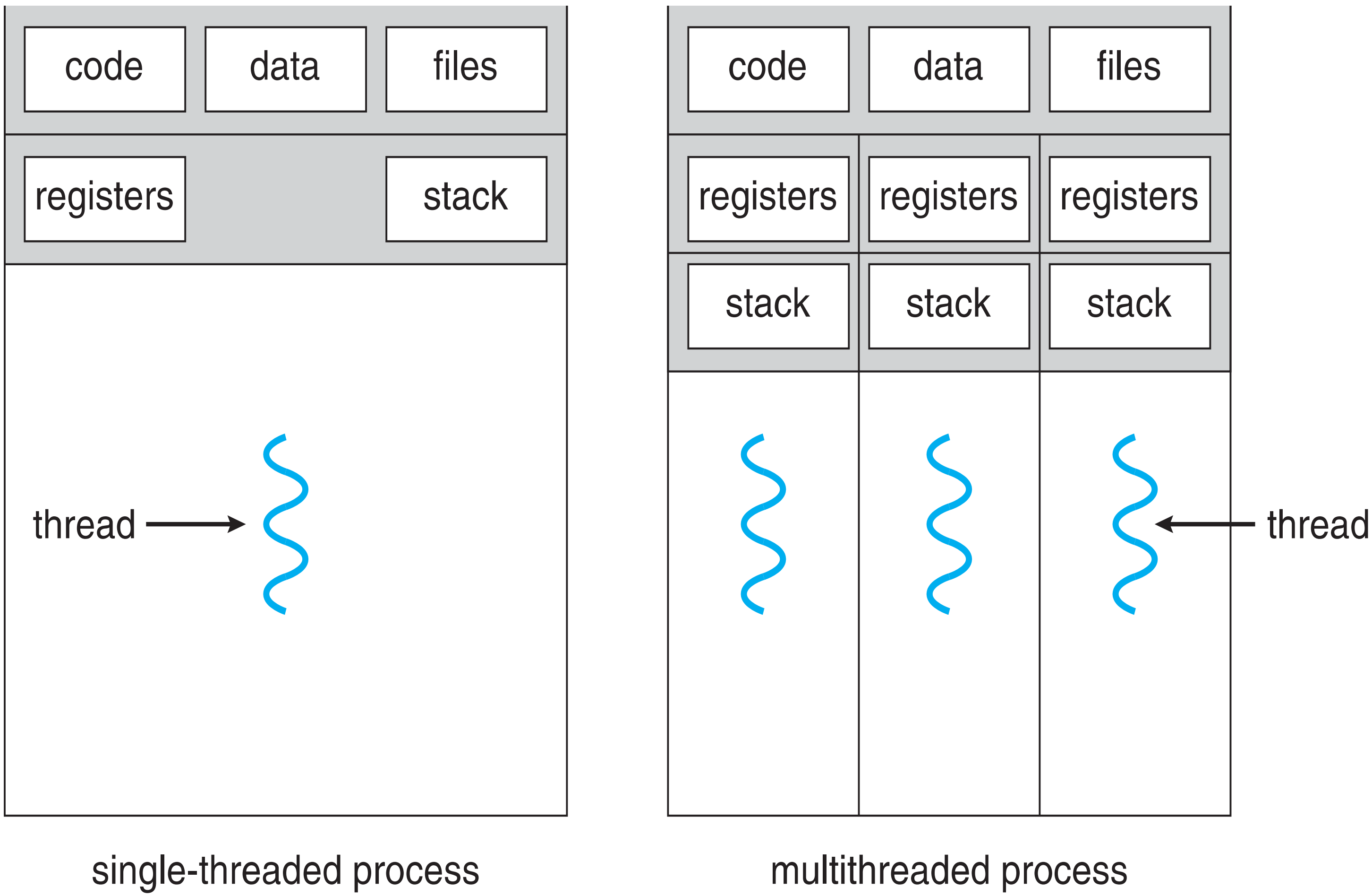
Parallel execution on a multi-core system:



Multi-threading

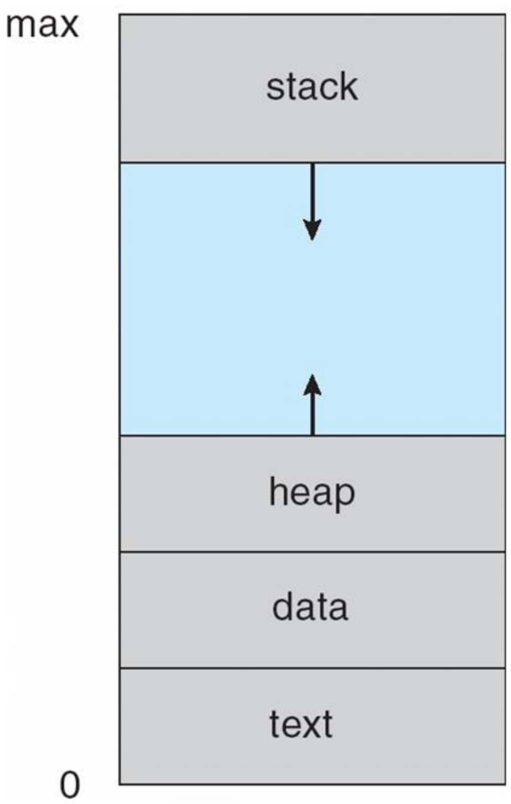
- Motivation
- Thread Concept

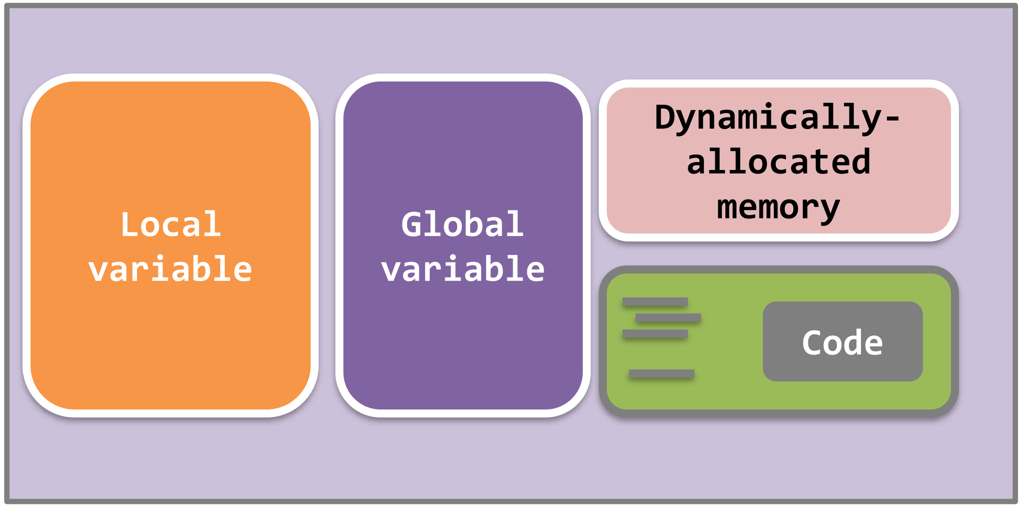
High-level Idea



Recall: Process in Memory

- User-space memory of Process A





Multi-thread – internals

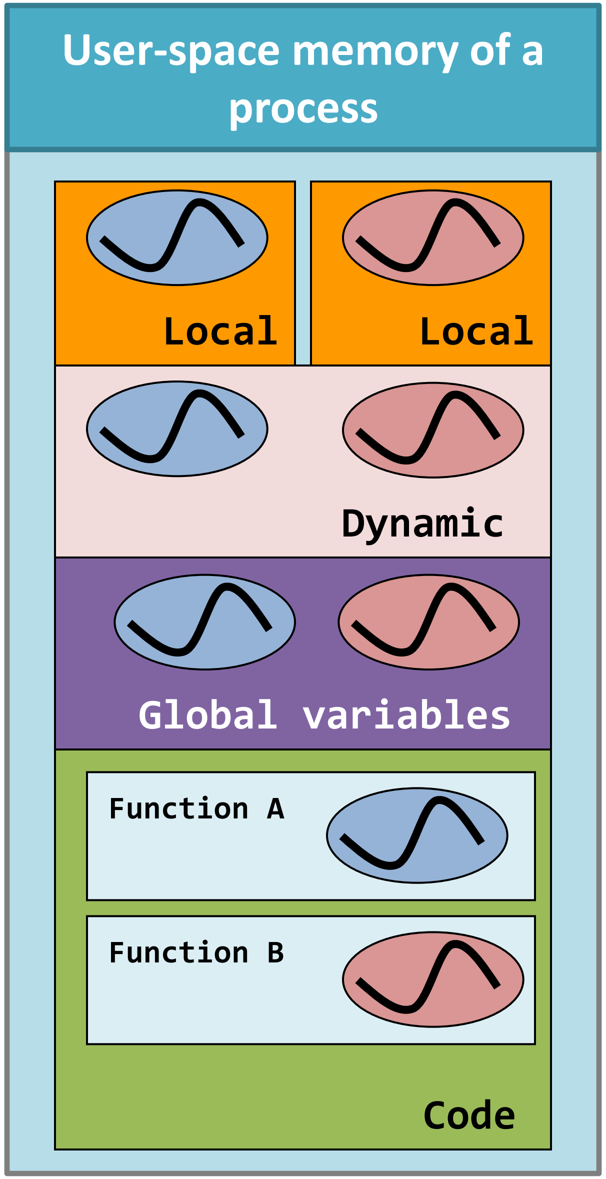
Code

- All threads **share** the same code.

- A thread starts with **one specific function**.
  - We name it the **thread function**
  - Functions A & B in the diagram

- The thread function can invoke other functions or system calls

- But, a thread could **never return to the caller of the thread function**.



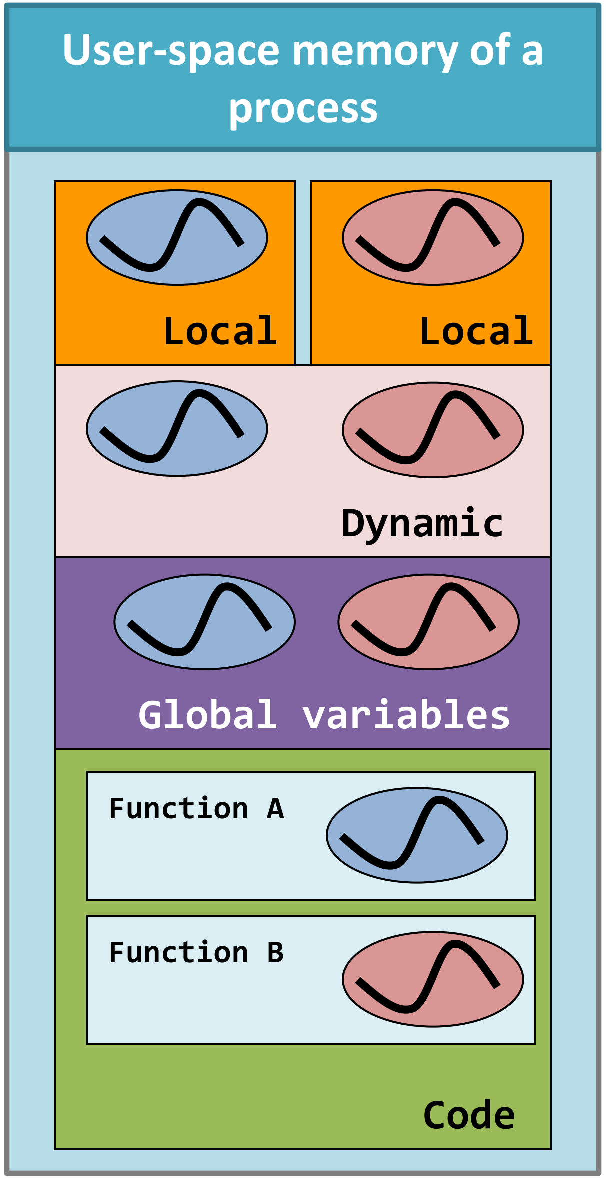
Multi-thread – internals

Dynamically allocated memory

Global variables

- All threads **share** the same **global variable zone** and the same **dynamically allocated memory**

- All threads can read from and write to both areas

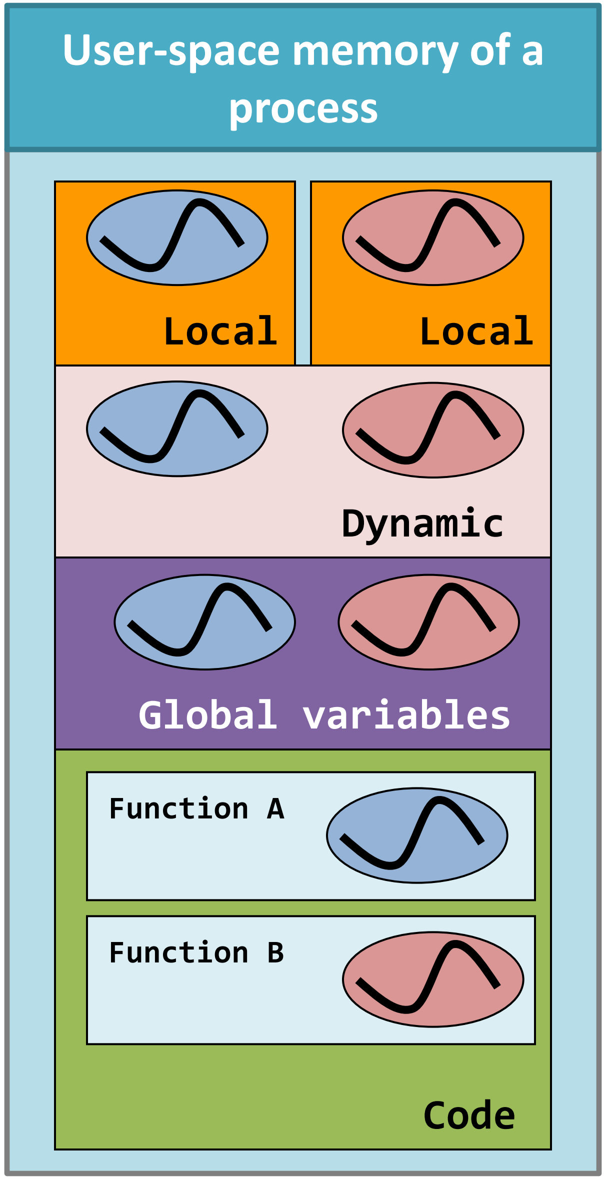


Multi-thread – internals

Local variables

- Each thread has **its own memory range** for the local variables

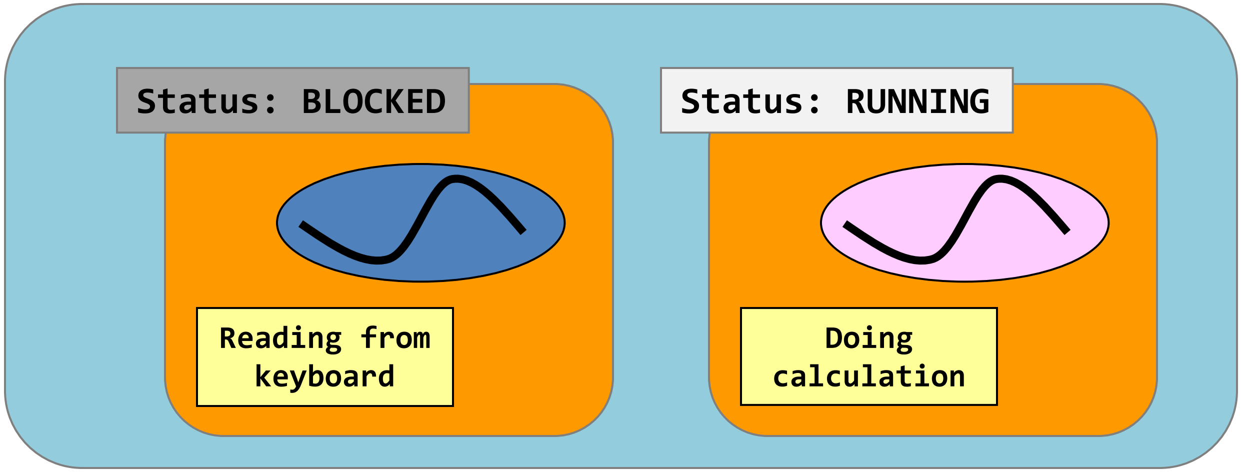
- So, the stack is the private zone for each stack



Benefits of Multi-thread

- **Responsiveness and multi-tasking**
  - Multi-threading design allows an application to do parallel tasks simultaneously
  - Example: Although a thread is blocked, the process can still depend on another thread to do other things!
  - Especially important for interactive applications (user interface)

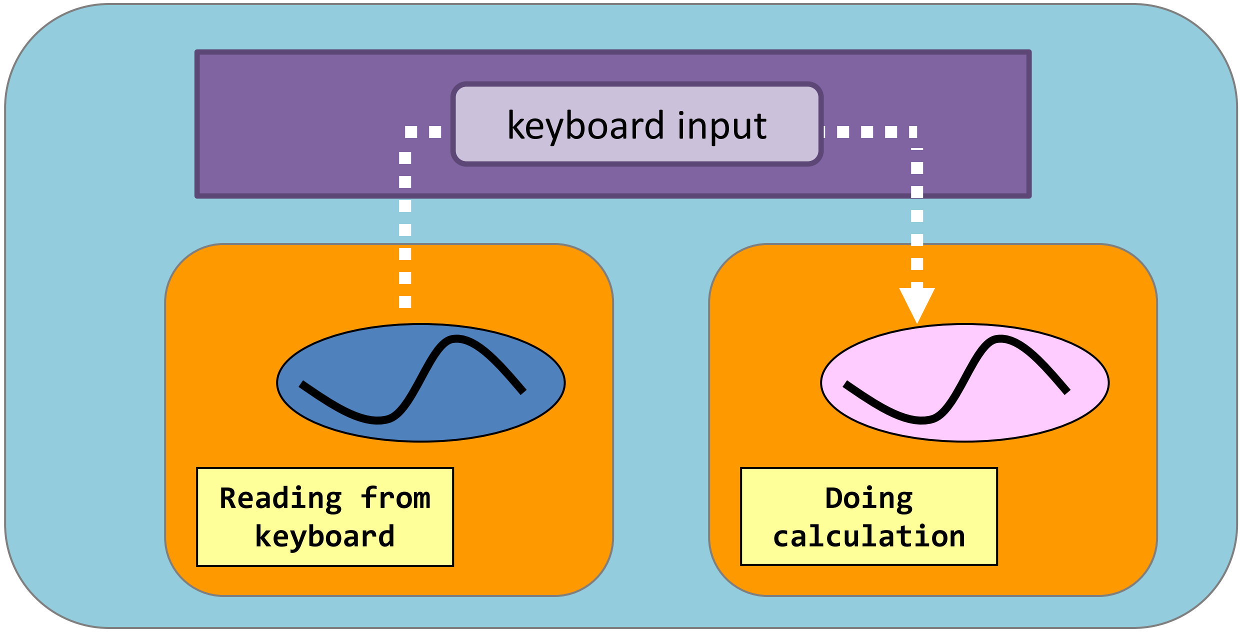
It'd be nice to assign **one thread for one blocking system/library call**.



Benefits of Multi-thread

- **Ease in data sharing**, can be done using:
  - global variables, and
  - dynamically allocated memory.
- Processes share resources via shared memory or message passing, which must be explicitly arranged by the programmer

Of course, this leads to the **mutual exclusion** & the **synchronization** problems (will be talked in later chapters)



Benefits of Multi-thread

- **Economy**
  - Allocating memory and resources for process creation is costly, dozens of times slower than creating threads
  - Context-switch between processes is also costly, several times of slower
- **Scalability**
  - Threads may be running in parallel on different cores

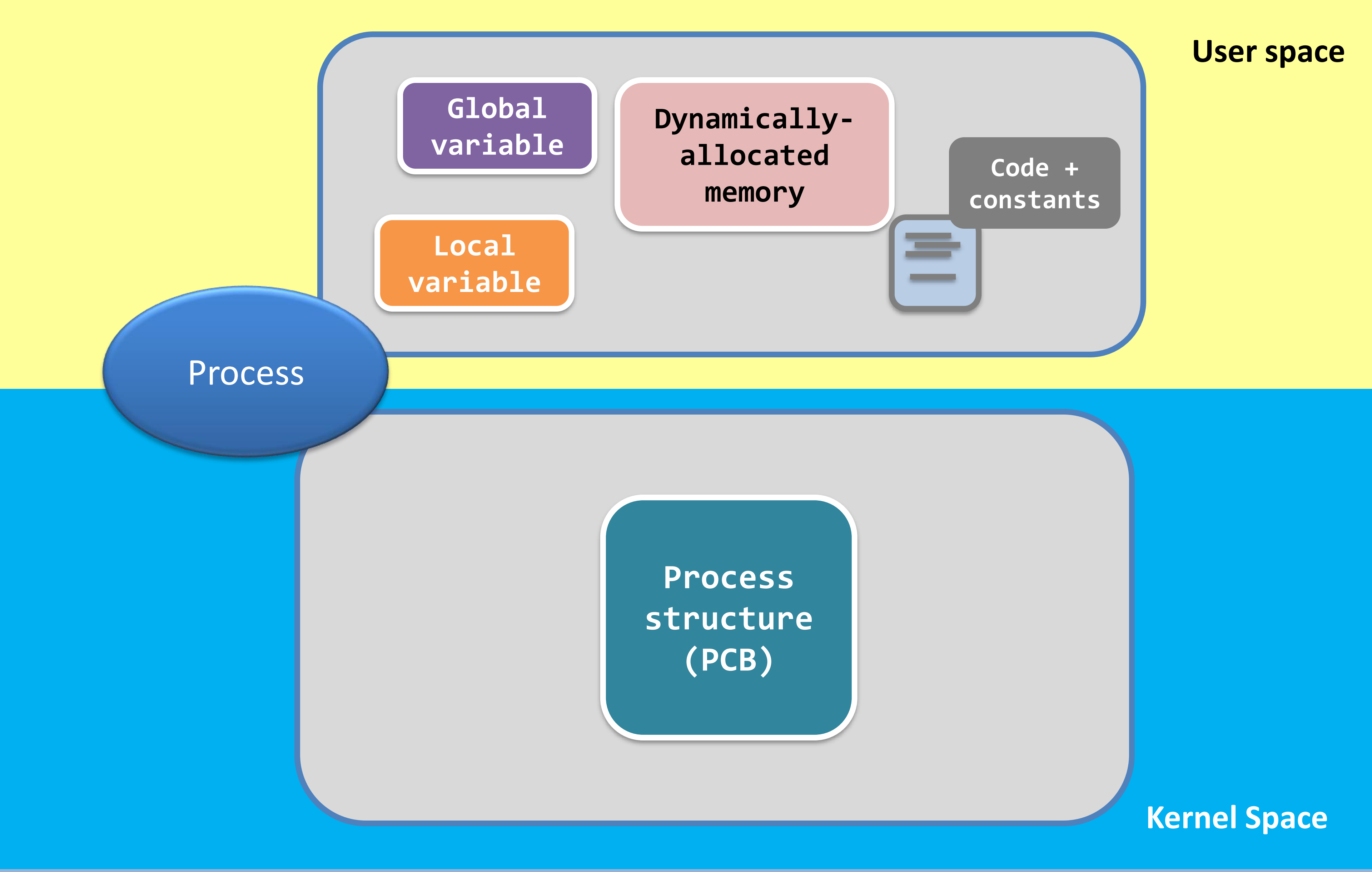
Programming Challenges

- **Identifying tasks**
  - Divide separate and concurrent tasks
- **Balance**
  - Tasks should perform equal work of equal value
- **Data splitting**
  - Data must be divided to run on separate cores
- **Data dependency**
  - Synchronization is needed
- **Testing and debugging**

Multi-threading

- Motivation
- Thread Concept
- Thread Models

Recall Process Structure



Similarly…

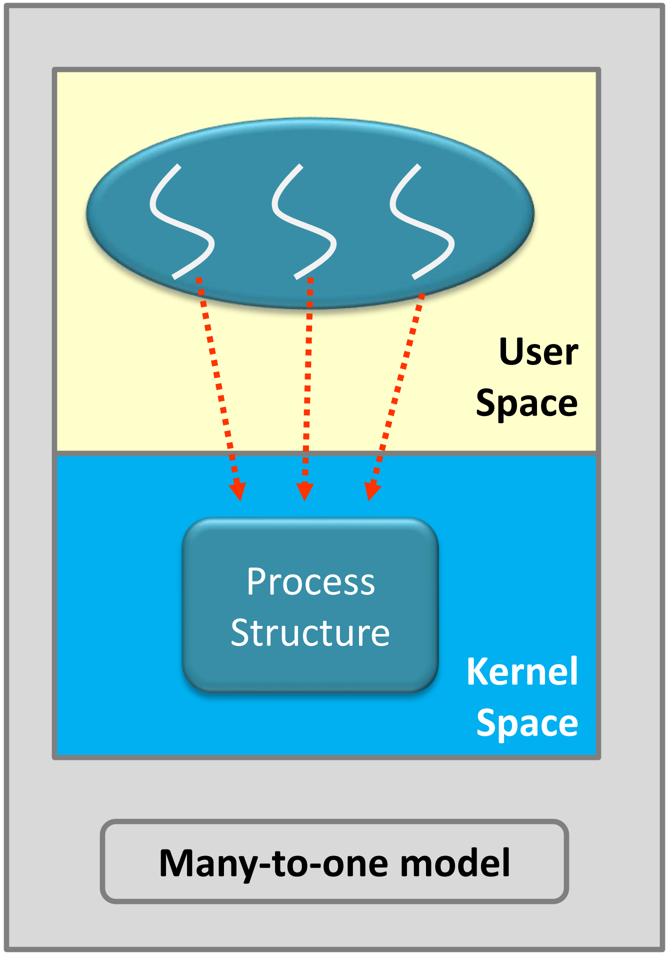
- Thread should also include
  - Data/resources in user-space memory
  - Structure in kernel

- How to provide thread support?
  - User thread
    - Implement in user space
  - Kernel thread
    - Supported and managed by kernel

- Thread models (relationship between user/kernel thread)
  - Many-to-one
  - One-to-one
  - Many-to-many

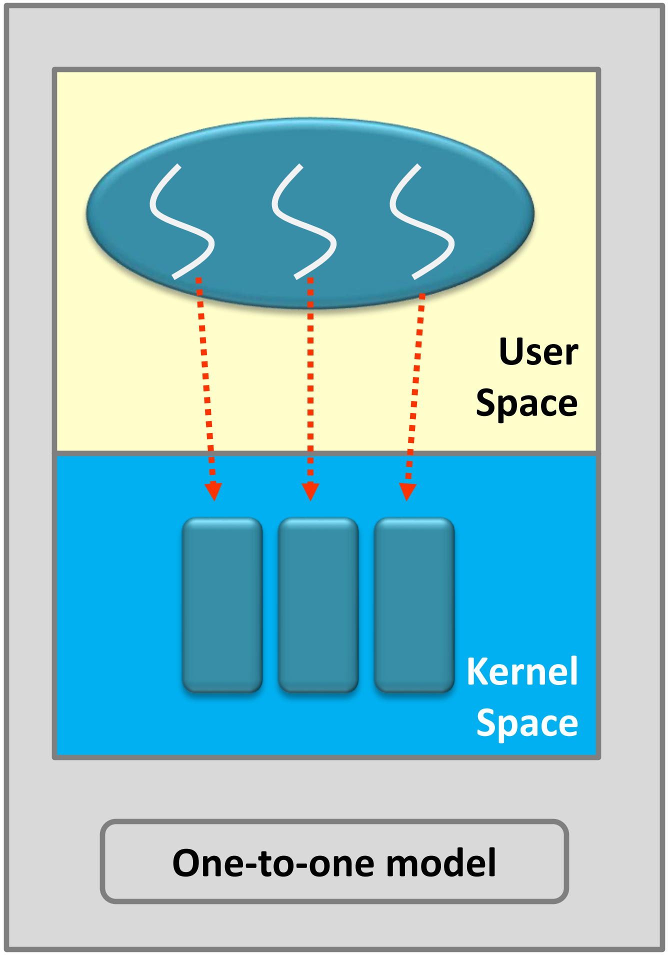
Thread models

- **Many-to-One Model**
  - All the threads are mapped to one process structure in the kernel.
  - Merit
    - Easy for the kernel to implement.
  - Drawback
    - When a blocking system call is called, all the threads will be blocked
  - **Example.** Old UNIX & green thread in some programming languages.



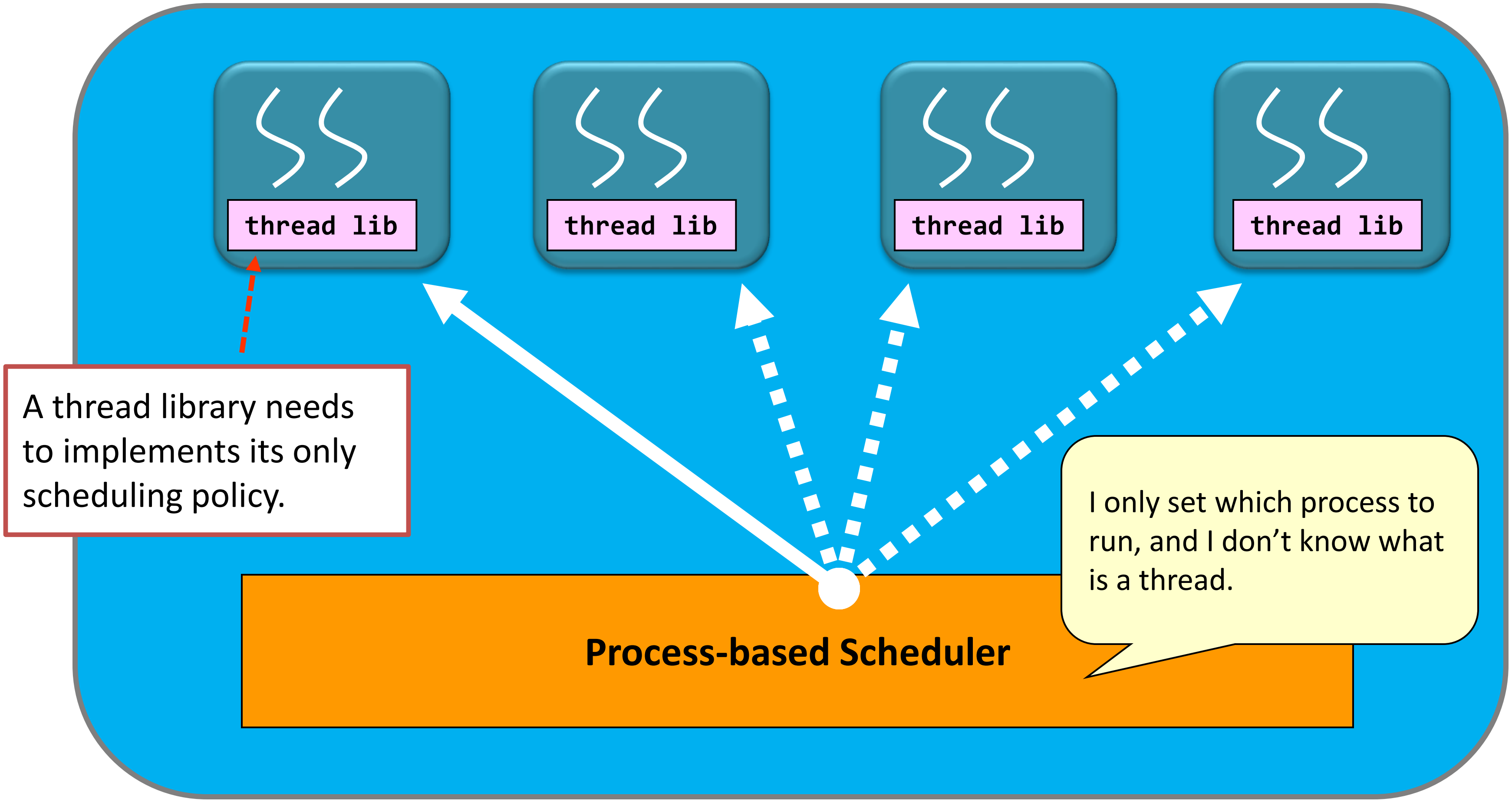
Thread models

- **<u>One-to-One Model</u>**
  - Each thread is mapped to a process or a thread structure
  - Merit:
    - Calling blocking system calls only block those calling threads
    - A high degree of concurrency
  - Drawback:
    - Cannot create too many threads as it is restricted by the size of the kernel memory
  - **<u>Example.</u>** Linux and Windows follow this thread model



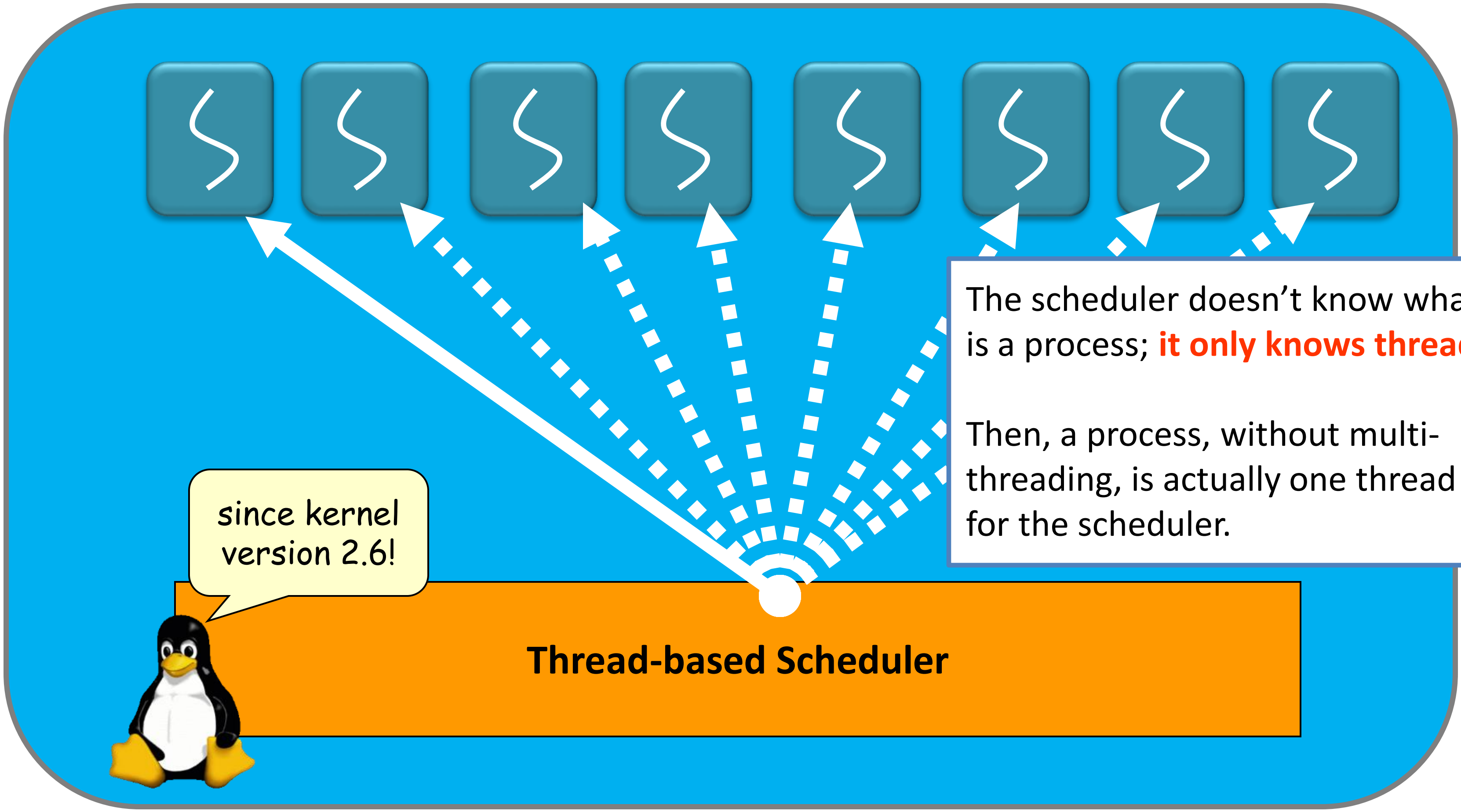
Scheduling – why & who cares?

- If a scheduler only interests in **processes**...



Scheduling – why & who cares?

- If a scheduler only interests in **threads**…

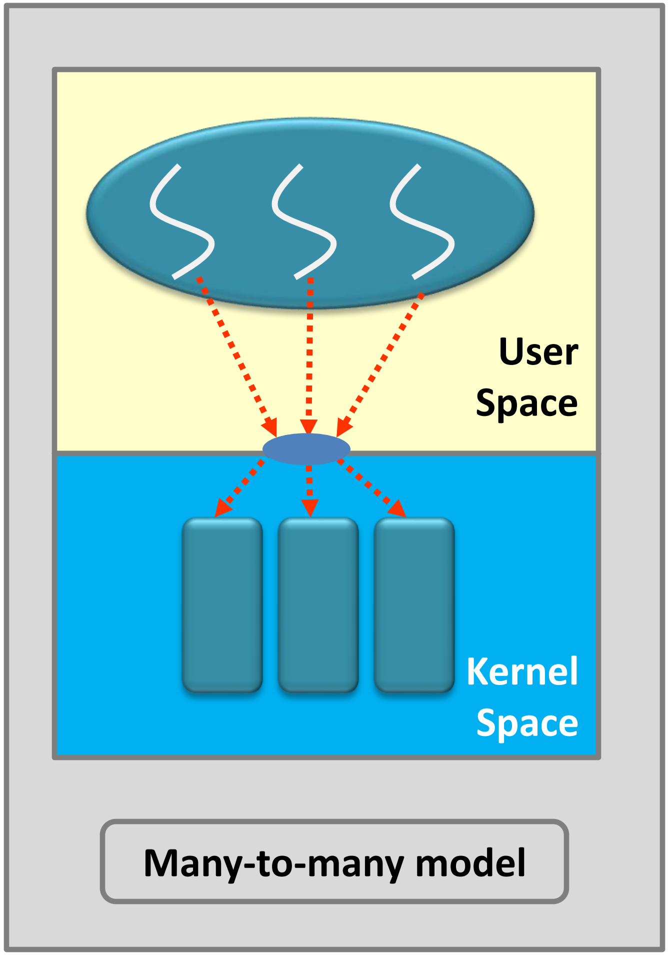


The scheduler doesn't know what is a process; **it only knows threads**.

Then, a process, without multi-threading, is actually one thread for the scheduler.

Thread models

- **<u>Many-to-many Model</u>**
  - Multiple threads are mapped to multiple structures (group mapping)
  - Merit:
    - Create as many threads as necessary
    - Also have a high degree of concurrency



Multi-threading

- Motivation
- Thread Concept
- Thread Models
- Basic Programming

Thread Libraries

- A thread library provides the programmer with an **API** for creating and managing threads
  - Two ways of implementation: User-level or kernel-level

- Three main thread libraries
  - POSIX Pthreads (user-level or kernel-level)
  - Windows (kernel-level)
  - Java (implemented using Windows API or Pthreads)

Creating Multiple Threads

- Asynchronous threading
  - Parent resumes execution after creating a child
  - Parent and child execute concurrently
  - Each thread runs independently
    - Little data sharing
- Synchronous threading
  - Fork-join strategy: Parent waits for children to terminate
    - Significant data sharing

The Pthreads Library

- **Pthreads**: POSIX standard defining an API for thread creation and synchronization.
  - Specification, not implementation
- How to use Pthreads?

	Process	Thread
Creation	`fork()`	`pthread_create()`
I.D. Type	`PID, an integer`	`“pthread_t”, a structure`
Who am I?	`getpid()`	`pthread_self()`
Termination	`exit()`	`pthread_exit()`
Wait for child termination	`wait() or waitpid()`	`pthread_join()`
Kill?	`kill()`	`pthread_kill()`

ISSUE 1: Thread Creation

Thread creation – **pthread_create()**

Thread Function

```
void * hello( void *input ) {
    printf("%s\n", (char *) input);
    pthread_exit(NULL);
}
```

Main Function

```
int main(void) {
    pthread_t tid;
    pthread_create(&tid, NULL, hello, "hello world");
    pthread_join(tid, NULL);
    return 0;
}
```

Thread creation – **pthread_create()**

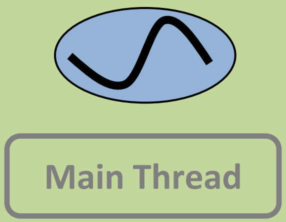
Thread Function

```c
void * hello( void *input ) {
    printf(“%s\n”, (char *) input);
    pthread_exit(NULL);
}
```

Main Function

```c
int main(void) {
    pthread_t tid;
    pthread_create(&tid, NULL, hello, “hello world”);
    pthread_join(tid, NULL);
    return 0;
}
```

At the beginning, there is only one thread running: **the main thread**.



Thread creation – **pthread_create()**

Thread Function

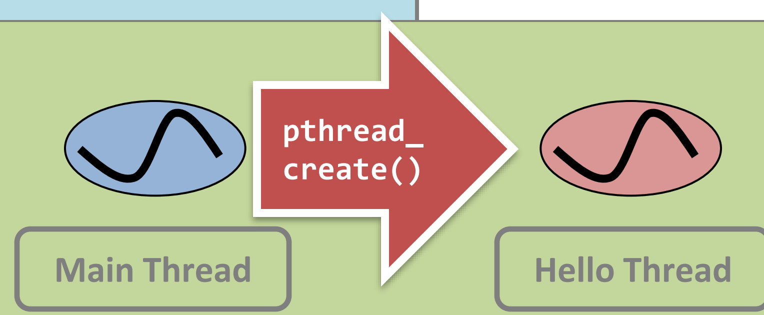
```
void * hello( void *input ) {
    printf("%s\n", (char *) input);
    pthread_exit(NULL);
}
```

Main Function

```
int main(void) {
    pthread_t tid;
    pthread_create(&tid, NULL, hello, "hello world");
    pthread_join(tid, NULL);
    return 0;
}
```

The hello thread is created!

It is running "*together*" with the main thread.



Thread creation – **pthread_create()**

Thread Function

```
void * hello( void *input ) {
    printf("%s\n", (char *) input);
    pthread_exit(NULL);
}
```

Main Function

```
int main(void) {
    pthread_t tid;
    pthread_create(&tid, NULL, hello, "hello world");
    pthread_join(tid, NULL);
    return 0;
}
```

The **pthread_create()** function allows one argument to be passed to the thread function.

This sets the thread function of the to-be-created thread as: **hello()**.

Remember: A thread starts with **one specific function (thread function)**

Thread creation – **pthread_create()**

Thread Function

```
void * hello( void *input ) {
      printf("%s\n", (char *) input);
      pthread_exit(NULL);
}
```

Main Function

```
int main(void) {
      pthread_t tid;
      pthread_create(&tid, NULL, hello, "hello world");
      pthread_join(tid, NULL);
      return 0;
}
```

Remember **wait()** and **waitpid()**?

pthread_join() performs similarly.

Thread creation – **pthread_create()**

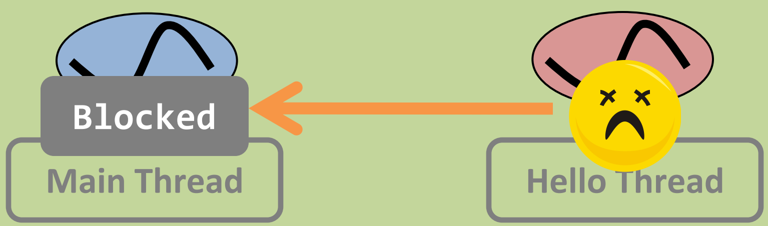
Thread Function

```
void * hello( void *input ) {
    printf("%s\n", (char *) input);
    pthread_exit(NULL);
}
```

Main Function

```
int main(void) {
    pthread_t tid;
    pthread_create(&tid, NULL, hello, "hello world");
    pthread_join(tid, NULL);
    return 0;
}
```

Termination of the target thread causes `pthread_join()` to return.



ISSUE 2: Passing parameters

Thread creation – passing parameter

Thread Function

```
void * do_your_job( void *input ) {
     printf(“child = %d\n”, *( (int *) input) );
     *((int *) input) = 20;
     printf(“child = %d\n”, *( (int *) input) );
     pthread_exit(NULL);
}
```

Main Function

```
int main(void) {
     pthread_t tid;
     int input = 10;
     printf(“main = %d\n”, input);
     pthread_create(&tid, NULL, do_your_job, &input);
     pthread_join(tid, NULL);
     printf(“main = %d\n”, input);
     return 0;
}
```

Guess: What is the output?

```
$ ./pthread_evil_1
main = 10
child = 10
child = 20
main = 20
$
```

Each thread has a separated stack.

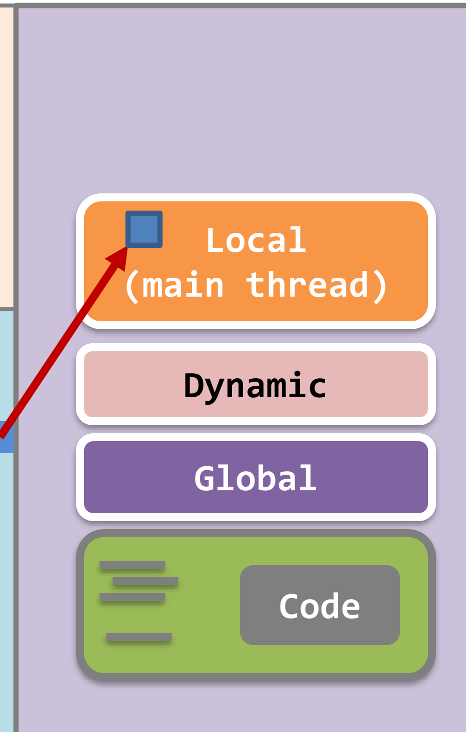
Why do we have such results?

Thread creation – passing parameter

Well, we all know that the local variable “**`input`**” is in **the stack for the main thread**.

```
void * do_your_job( void *input ) {
    printf(“child = %d\n”, *( (int *) input) );
    *((int *) input) = 20;
    printf(“child = %d\n”, *( (int *) input) );
    pthread_exit(NULL);
}

int main(void) {
    pthread_t tid;
    int input = 10;
    printf(“main = %d\n”, input);
    pthread_create(&tid, NULL, do_your_job, &input);
    pthread_join(tid, NULL);
    printf(“main = %d\n, input);
    return 0;
}
```

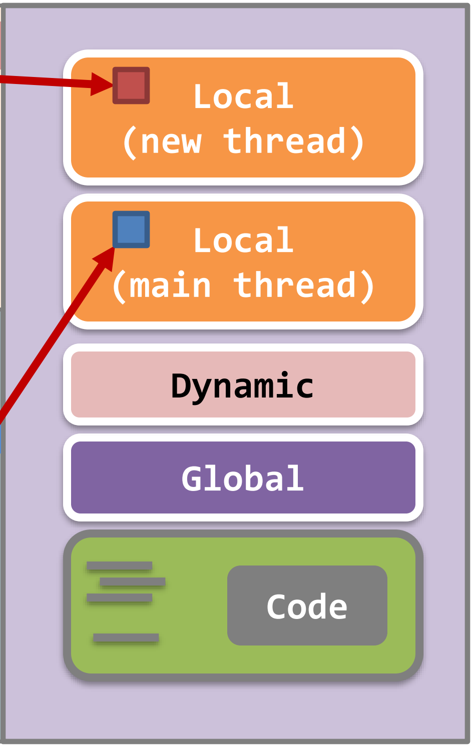


Thread creation – passing parameter

Yet…the stack for the new thread is not on another process, but is **<u>on the same piece of user-space memory as the main thread</u>**.

```
void * do_your_job( void *input ) {
    printf(“child = %d\n”, *( (int *) input) );
    *((int *) input) = 20;
    printf(“child = %d\n”, *( (int *) input) );
    pthread_exit(NULL);
}

int main(void) {
    pthread_t tid;
    int input = 10;
    printf(“main = %d\n”, input);
    pthread_create(&tid, NULL, do_your_job, &input);
    pthread_join(tid, NULL);
    printf(“main = %d\n, input);
    return 0;
}
```

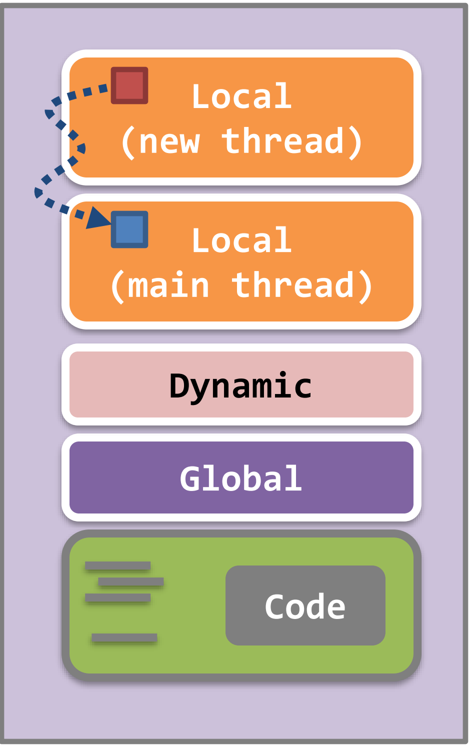


Thread creation – passing parameter

The **pthread_create()** function only passes an **address** to the new thread. Worse, the address is **pointing to a variable in the stack of the main thread**!

```
void * do_your_job( void *input ) {
    printf(“child = %d\n”, *( (int *) input) );
    *((int *) input) = 20;
    printf(“child = %d\n”, *( (int *) input) );
    pthread_exit(NULL);
}

int main(void) {
    pthread_t tid;
    int input = 10;
    printf(“main = %d\n”, input);
    pthread_create(&tid, NULL, do_your_job, &input);
    pthread_join(tid, NULL);
    printf(“main = %d\n, input);
    return 0;
}
```

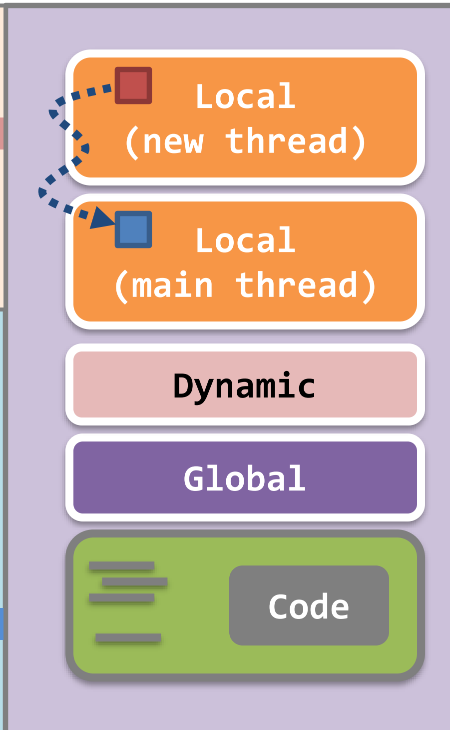


Thread creation – passing parameter

Therefore, the new thread can change the value in the main thread, and **vice versa**.

```
void * do_your_job( void *input ) {
    printf(“child = %d\n”, *( (int *) input) );
    *((int *) input) = 20;
    printf(“child = %d\n”, *( (int *) input) );
    pthread_exit(NULL);
}

int main(void) {
    pthread_t tid;
    int input = 10;
    printf(“main = %d\n”, input);
    pthread_create(&tid, NULL, do_your_job, &input);
    pthread_join(tid, NULL);
    printf(“main = %d\n, input);
    return 0;
}
```



ISSUE 3: Multiple Threads

Thread creation – multiple threads

Thread Function

```
void * do_your_job(void *input) {
    int id = *((int *) input);
    printf("My ID number = %d\n", id);
    pthread_exit(NULL);
}
```

Main Function

```
int main(void) {
    int i;
    pthread_t tid[5];

    for(i = 0; i < 5; i++)
        pthread_create(&tid[i], NULL, do_your_job, &i);
    for(i = 0; i < 5; i++)
        pthread_join(tid[i], NULL);
    return 0;
}
```

Waiting on several threads: enclose pthread_join() within a for loop

ISSUE 4: Return Value

Thread termination – passing return value

Thread Function

```
void * do_your_job(void *input) {
    int *output = (int *) malloc(sizeof(int));
    srand(time(NULL));
    *output = ((rand() % 10) + 1) * (*((int *) input));
    pthread_exit( output );
}
```

Main Function

```
int main(void) {
    pthread_t tid;
    int input = 10, *output;
    pthread_create(&tid, NULL, do_your_job, &input);
    pthread_join(tid, (void **) &output );
    return 0;
}
```

`void pthread_exit(void *return_value);`

Together with termination, a pointer to a global variable or a piece of dynamically allocated memory is returned to the main thread.

Using pass-by-reference, a pointer to the result is received in the main thread.

Other Libraries

- For Windows threads and Java threads, you can refer to the textbook if you are interested in.

Multi-threading

- Motivation
- Thread Concept
- Thread Models
- Basic Programming
- Implicit Threading

Implicit Threading

- Applications are containing hundreds or even thousands of threads
  - Program correctness is more difficult with explicit threads
- How to address the programming difficulties?
  - Transfer the creation and management of threading from programmers to compilers and run-time libraries
  - Implicit threading
- We will introduce two methods
  - Thread Pools
  - OpenMP

Thread Pools

- Problems with multithreaded servers
  - Time required to create threads, which will be discarded once completed their work
  - Unlimited threads could exhaust the system resources
- How to solve?
  - Thread pool
  - Idea
    - Create a number of threads in a pool where they wait for work
  - Procedure
    - Awakens a thread if necessary
    - Returns to the pool after completion
    - Waits until one becomes free if the pool contains no available thread

Thread Pools

- Advantages
  - Usually slightly faster to service a request with an existing thread than create a new thread
  - Allows the number of threads in the application(s) to be bound to the size of the pool

OpenMP

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

```
#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;
}
```

Parallel for loop

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

When OpenMP encounters the directive, it creates as many threads as there are processing cores

Multi-threading

- Motivation
- Thread Concept
- Thread Models
- Basic Programming
- Implicit Threading
- Threading Issues

Semantics of `fork()` and `exec()`

- Two key system calls for processes: **`fork`**,**`exec`**

- **`fork()`**: Some UNIX systems have two versions
  - The new process duplicates all threads, or
  - Duplicates only the thread that invoked **`fork()`**

- **`exec()`**: usually works as normal
  - Replace the running process - including **all threads**

Signal Handling

- **Signals** are used in UNIX systems to notify a process that a particular event has occurred
  – Synchronous signal and asynchronous signal
  – Default handler or user-defined handler

- Where should a signal be delivered in multi-threaded program?
  – 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 for the process

- Deliver a signal to a specified thread with Pthread
  – `pthread_kill(pthread_t tid, int signal)`

Thread Cancellation

- Terminating a thread before it has finished
  - Why needed?
  - Example: Close a browser when multiple threads are loading images
- Two general approaches
  - **Asynchronous cancellation** terminates the target thread immediately
    - Problem: Troublesome when canceling a thread which is updating data shared by other threads
  - **Deferred cancellation** allows the target thread to periodically check if it should be cancelled (can be canceled safely)

Thread Cancellation (Cont.) - Pthreads

- Pthreads code example
  - **pthread_cancel()**
  - Indicates only a request

```
pthread_t tid;

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

. . .

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

- Three cancelation modes

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

- Default: deferred
  - Cancelation occurs only when it reaches a cancelation point, can be established by **pthread_testcancel()**

Thread-Local Storage

- Some applications, each thread may need its own copy of certain data
  - Transaction processing system: service each transaction (with a unique identifier) in a thread
  - How about local variables?
    - Visible only during a single function invocation
- Thread-local storage (TLS) allows each thread to have its own copy of data
  - TLS is visible across function invocations
  - Similar to **`static`** data
  - TLS data are unique to each thread

Summary of Threads

- Virtually all modern OSes support multi-threading
  - A thread is a basic unit of CPU utilization
  - Each comprises a thread ID, a program counter, a register set, and a stack
  - All threads within a process share code section, data section, other resources like open files and signals

- You should **take great care** when writing multi-threaded programs

- You also have to take care of (will be talked later):
  - Mutual exclusion and
  - Synchronization

End of Chapter 4