Operating System Concepts

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Chapter 4: Threads & Concurrency

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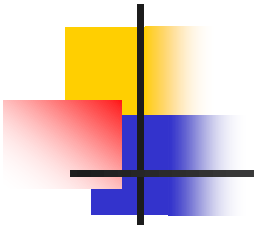
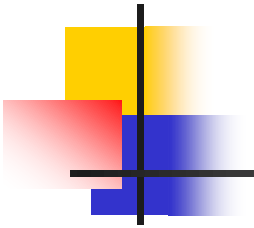
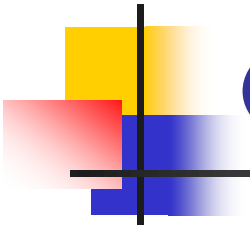


- **A process is defined by the resources it uses and by the location at which it is executing.**
- **Processes serve 4 roles:**
  - Unit of resource allocation
  - Memory context
  - Program that is being executed
  - Unit of activity
- **What do you do if your program wants to do more than one thing at a time ?**

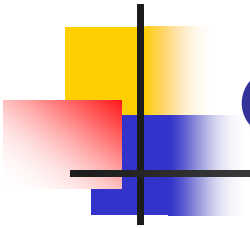


- The process model introduced in Chapter 3 assumed that a process was an executing program with a single thread of control.
- Modern OSes now provide features for a process to contain multiple threads of control.
- If a process has multiple threads of control, it can perform more than one task at a time.



Chapter Objectives

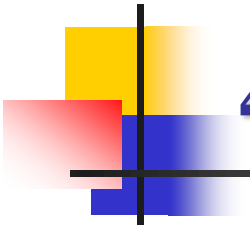
- Identify the basic components of a thread, and contrast threads and processes
- Describe the benefits and challenges of designing multithreaded applications
- Illustrate different approaches to implicit threading including thread pools, fork-join, and Grand Central Dispatch
- Describe how the Windows and Linux OSes represent threads
- Design multithreaded applications using the Pthreads, Java, and Windows threading APIs



Chapter 4: Threads & Concurrency

Outline

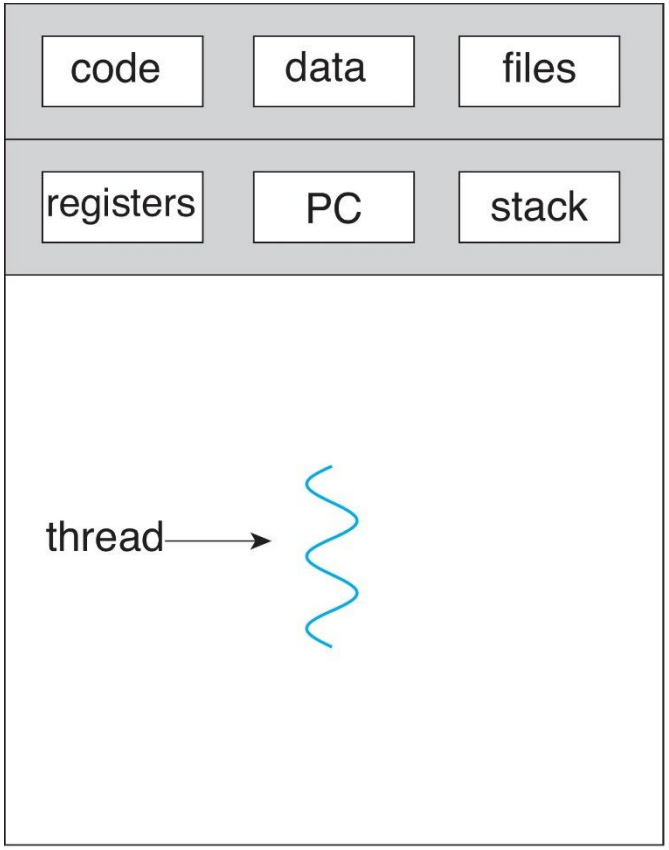
- 4.1 Overview
- 4.2 Multicore Programming
- 4.3 Multithreading Models
- 4.4 Thread Libraries
- 4.5 Implicit Threading
- 4.6 Threading Issues
- 4.7 Operating-System Examples



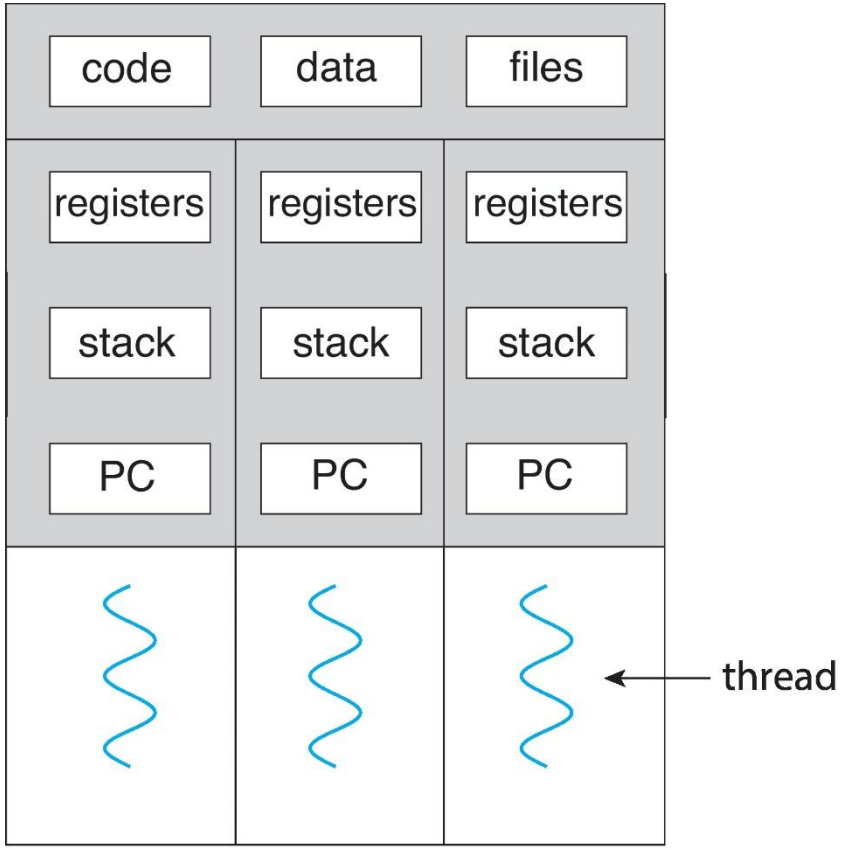
4.1 Overview

- **A *thread* is a basic unit of CPU utilization, comprises**
  - a thread ID, a program counter, a register set, and a stack
- **A thread shares with other threads belonging to the same process its**
  - code section
  - data section
  - other OS resources (open files, signals)
- **A traditional process has a single thread of control. If a process has multiple threads of control, it can perform more than one task at a time.**

Single-threaded and multithreaded processes (Fig. 4.1)



single-threaded process



multithreaded process

4.1.1 Motivation

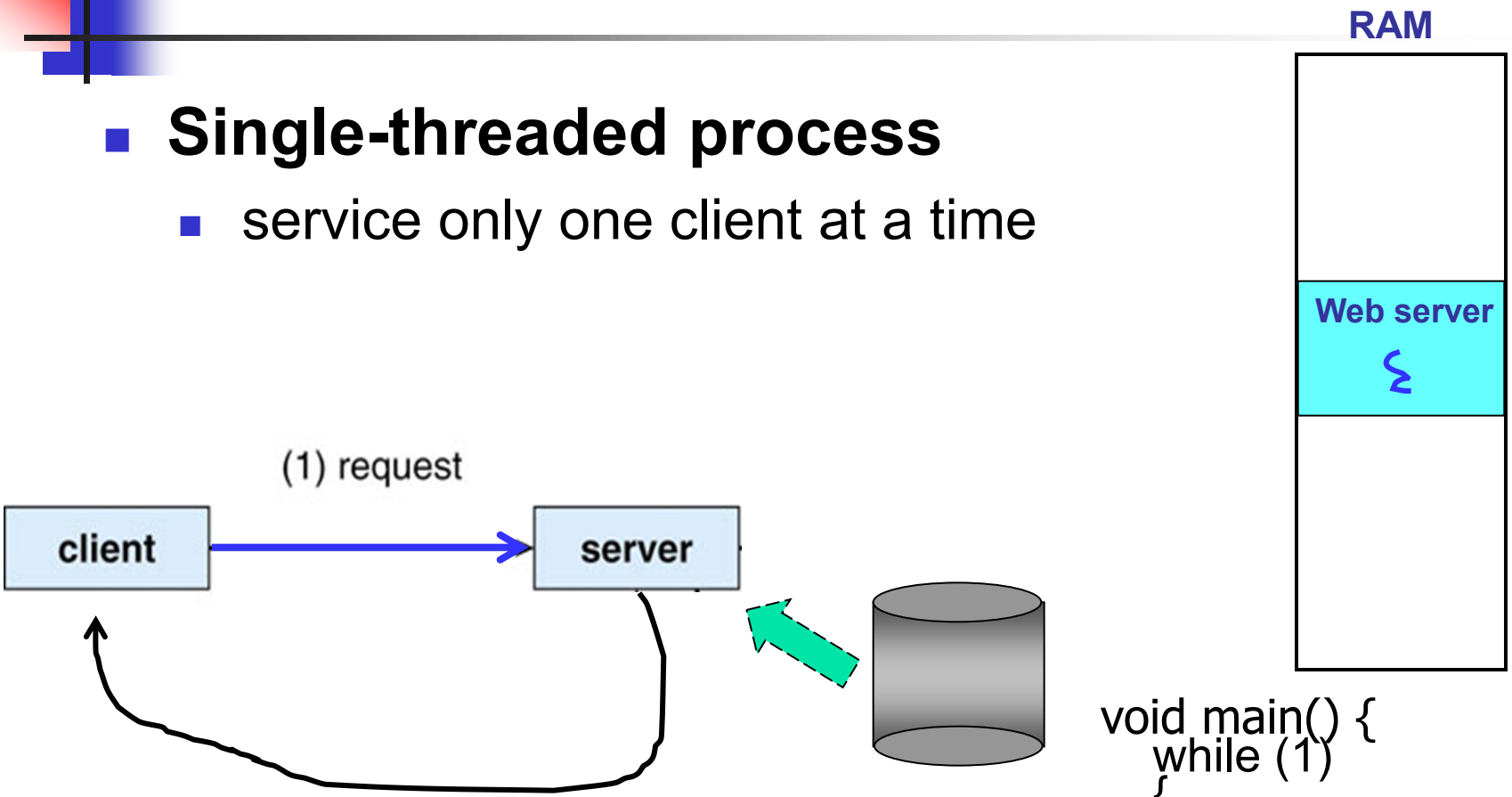
- **Most software applications that run on modern computers and mobile devices are multithreaded.**
- **An application typically is implemented as a separate process with several threads of control.**
- **Example: a web browser**
  - a thread displays images or text while another thread retrieves data from the network
- **Example: a word processor**
  - a thread for displaying graphics, a thread for responding keystrokes from the user, and a thread for performing spelling and grammar checking in the background
- **Example:**
  - applications can be designed and perform several CPU-intensive tasks in parallel on multicore systems.

Motivation (Cont.)

- **In certain situations a single application may be required to perform several similar tasks.**
- **Example: web server**
  - Single-threaded process: service only one client at a time
  - Multiple processes
  - multi-threaded process
    - One process that contains multiple threads to serve the same purpose.
- **Process creation is time consuming and resource intensive.**
- **If the new process will perform the same tasks as the existing process, it is generally more efficient for one process that contains multiple threads to serve the same purpose.**

Example: Web Server

- **Single-threaded process**
  - service only one client at a time

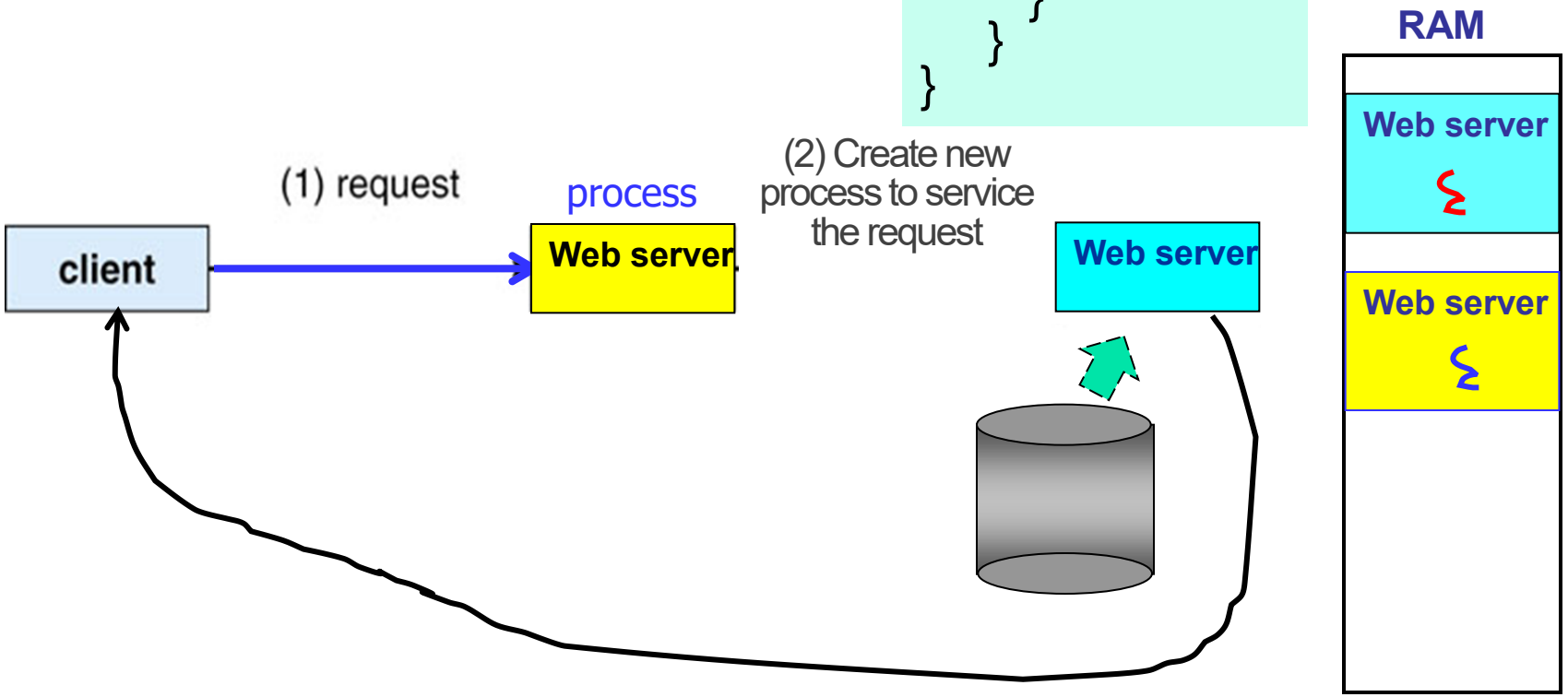



```
void main() {
   while (1)
   {
      receive();
      disk read;
      send();
   }
}
```

Example: Web Server

- **Multiple processes**

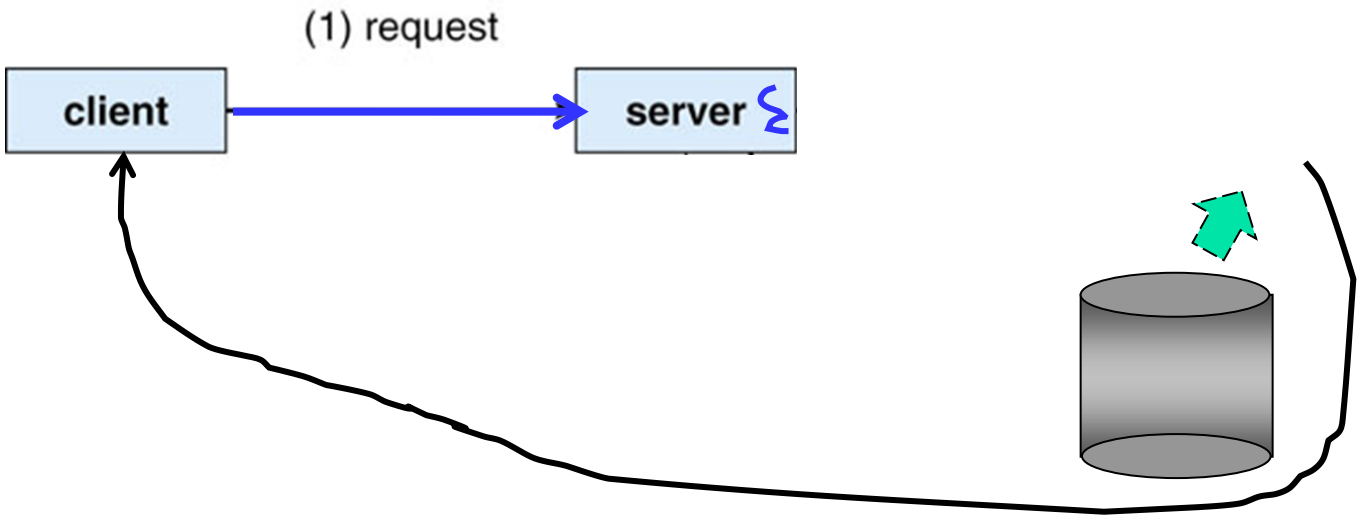
```
void main() {
    while (1)
    {
        receive();
        pid=fork();
        if (pid==0) {
            disk read;
            send();
            exit(0);
        }
    }
}
```

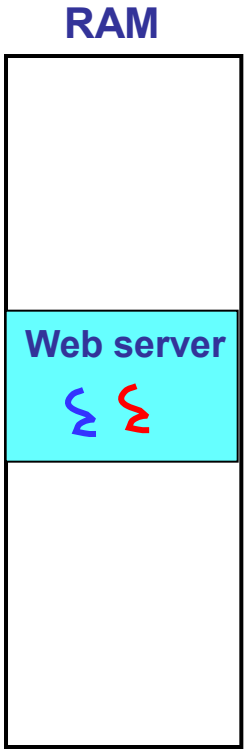


Multithreaded server architecture

- ***Multithreading a web server process***

```
void fun() {
   disk read;
   send();
   thread_exit(0);
}
void main() {
   while (1)
   {
     receive();
     createthread(fun);
   }
}
```





Motivation (Cont.)

- **In a multiple threaded process, while one thread is blocked and waiting, a second thread in the same task can run.**
  - Cooperation of multiple threads in the same job confers higher throughput and improved performance.
  - Applications that require sharing a common buffer (i.e., producer-consumer) benefit from thread utilization.

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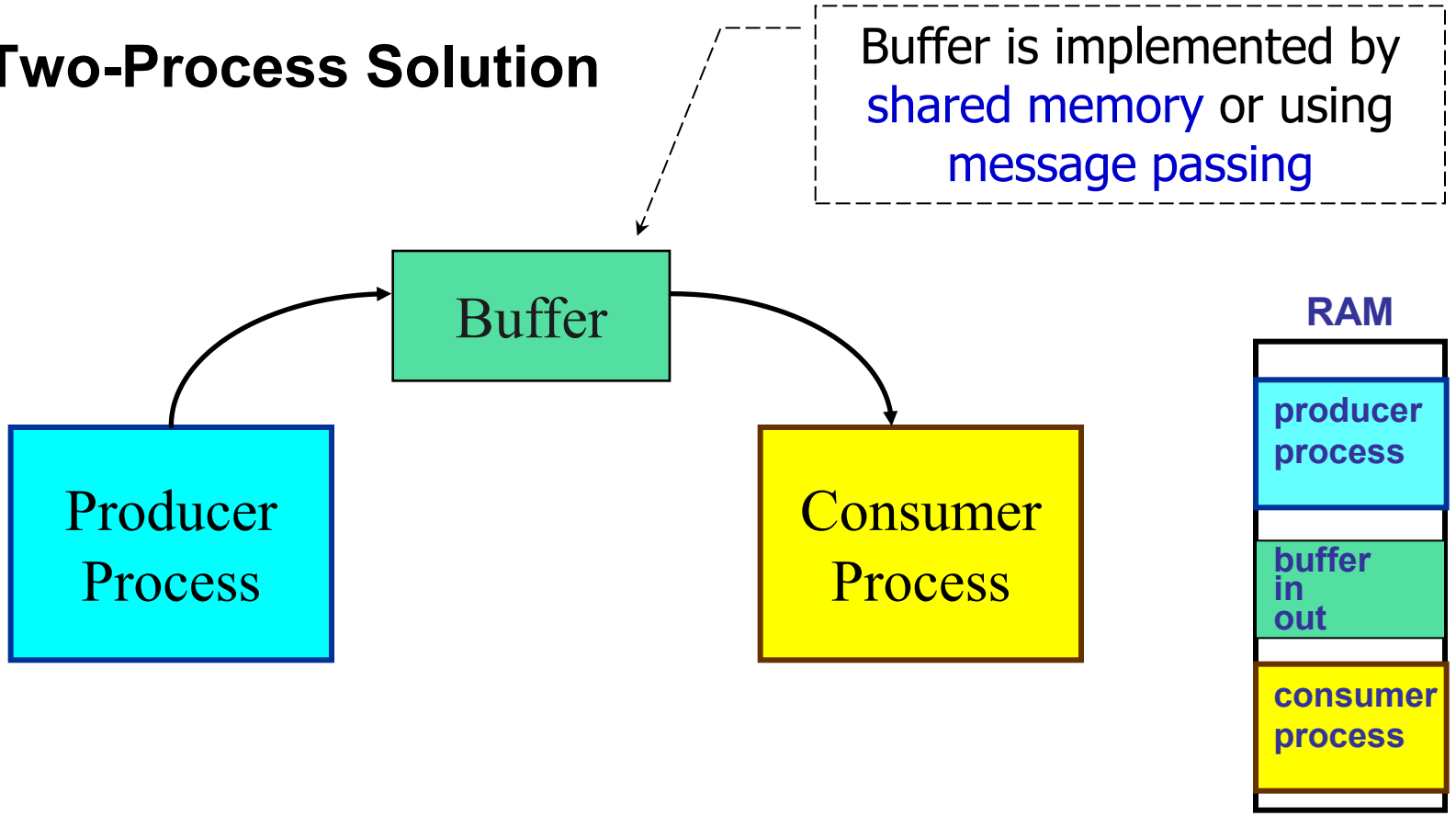
A Buffering Problem

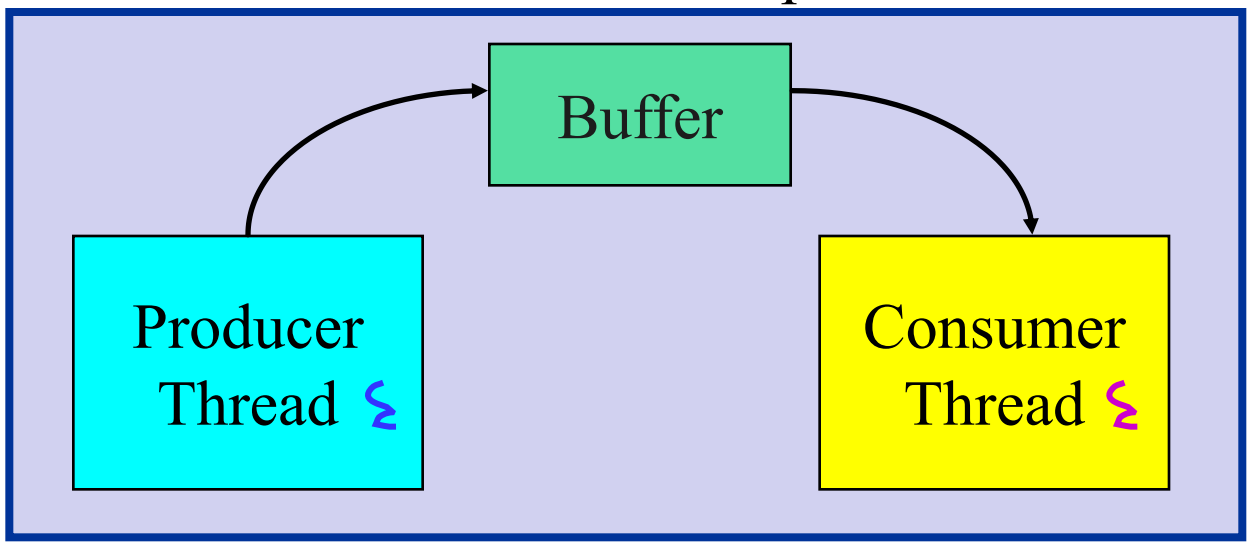
- **Two-Process Solution**

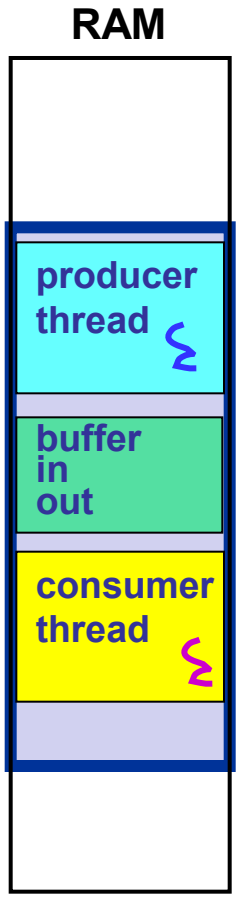


A Buffering Problem

- **Two-Thread Solution**

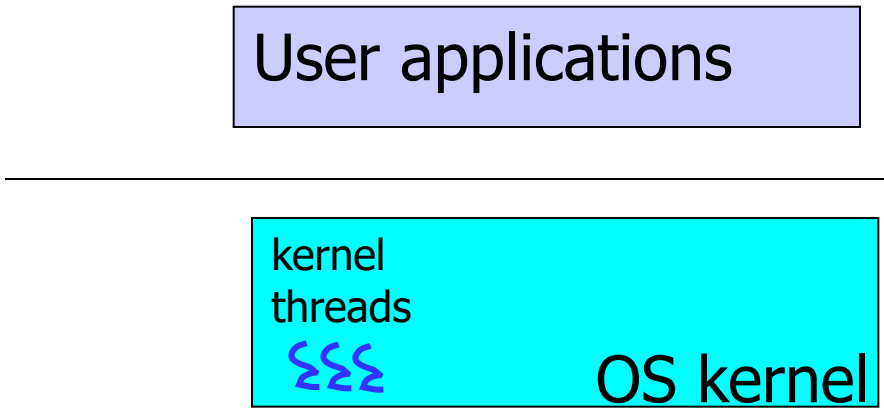
One process with 2 threads



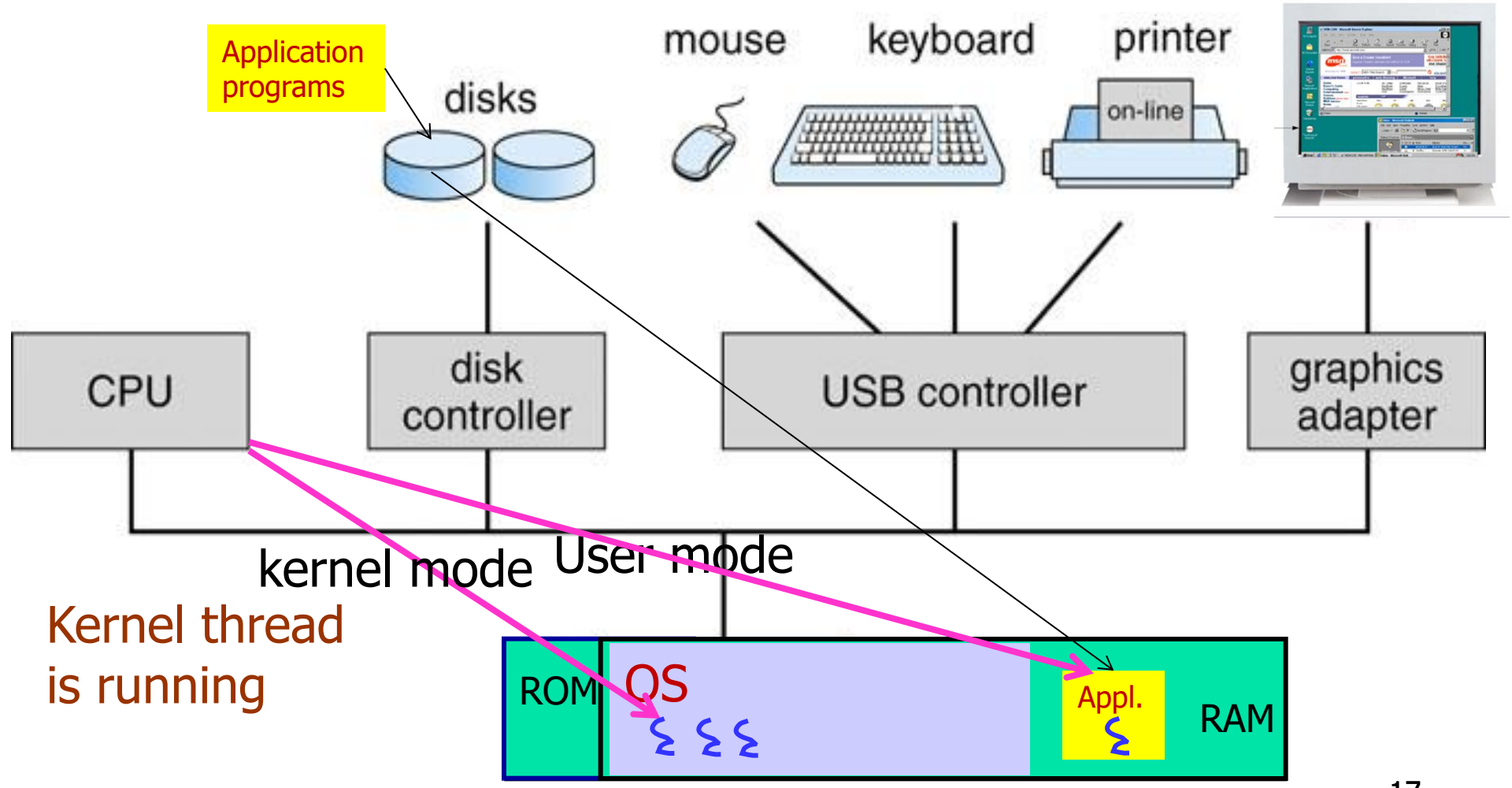


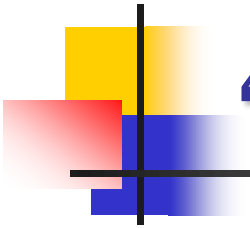
Motivation (Cont.)

- Most OS kernels are also typically multithreaded.
- Example: During boot time on Linux systems, several threads are created. Each thread performs a specific task, such as managing devices, managing memory, or interrupt handling.



When does an OS run?
(5) kernel thread

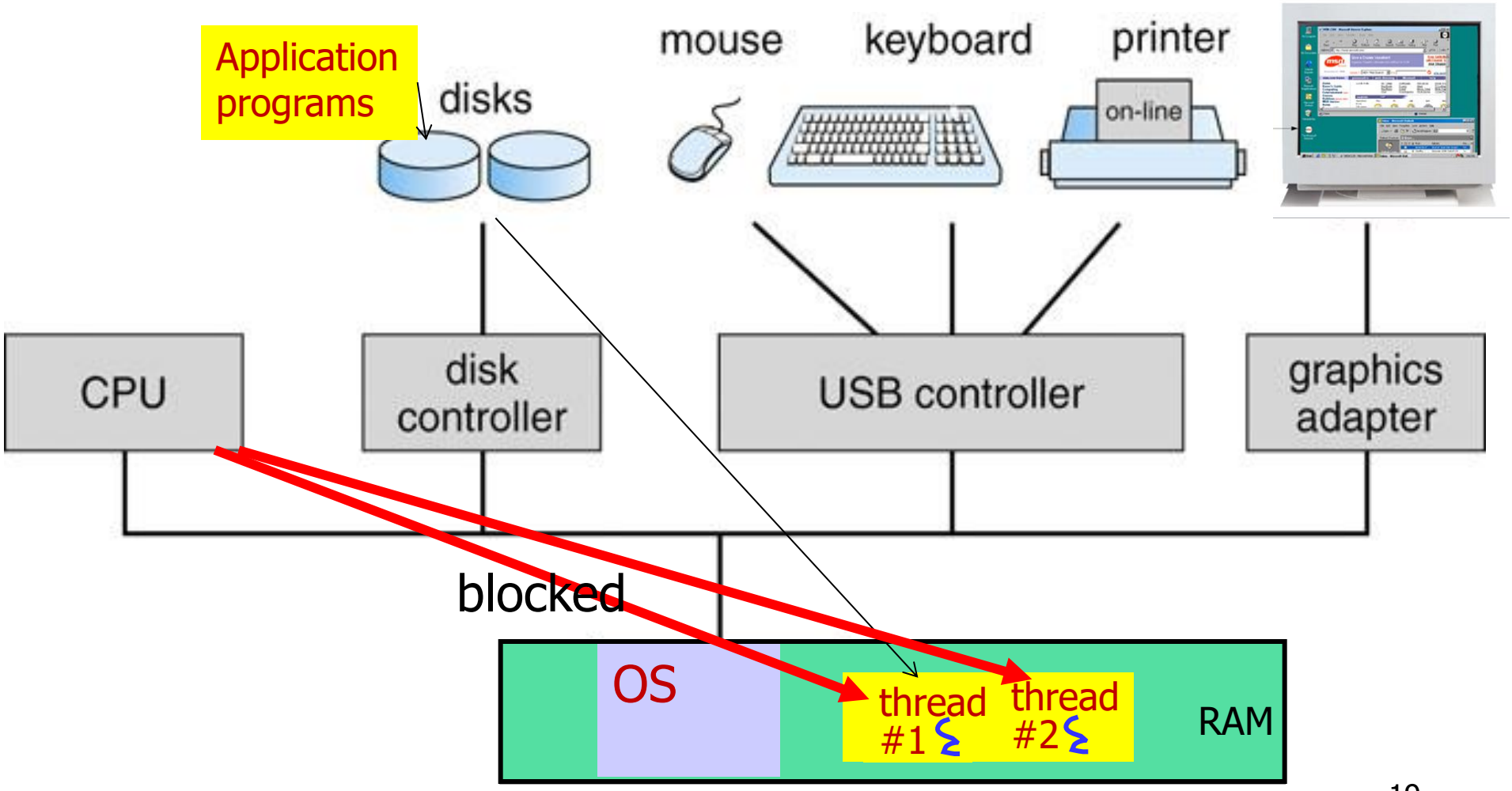




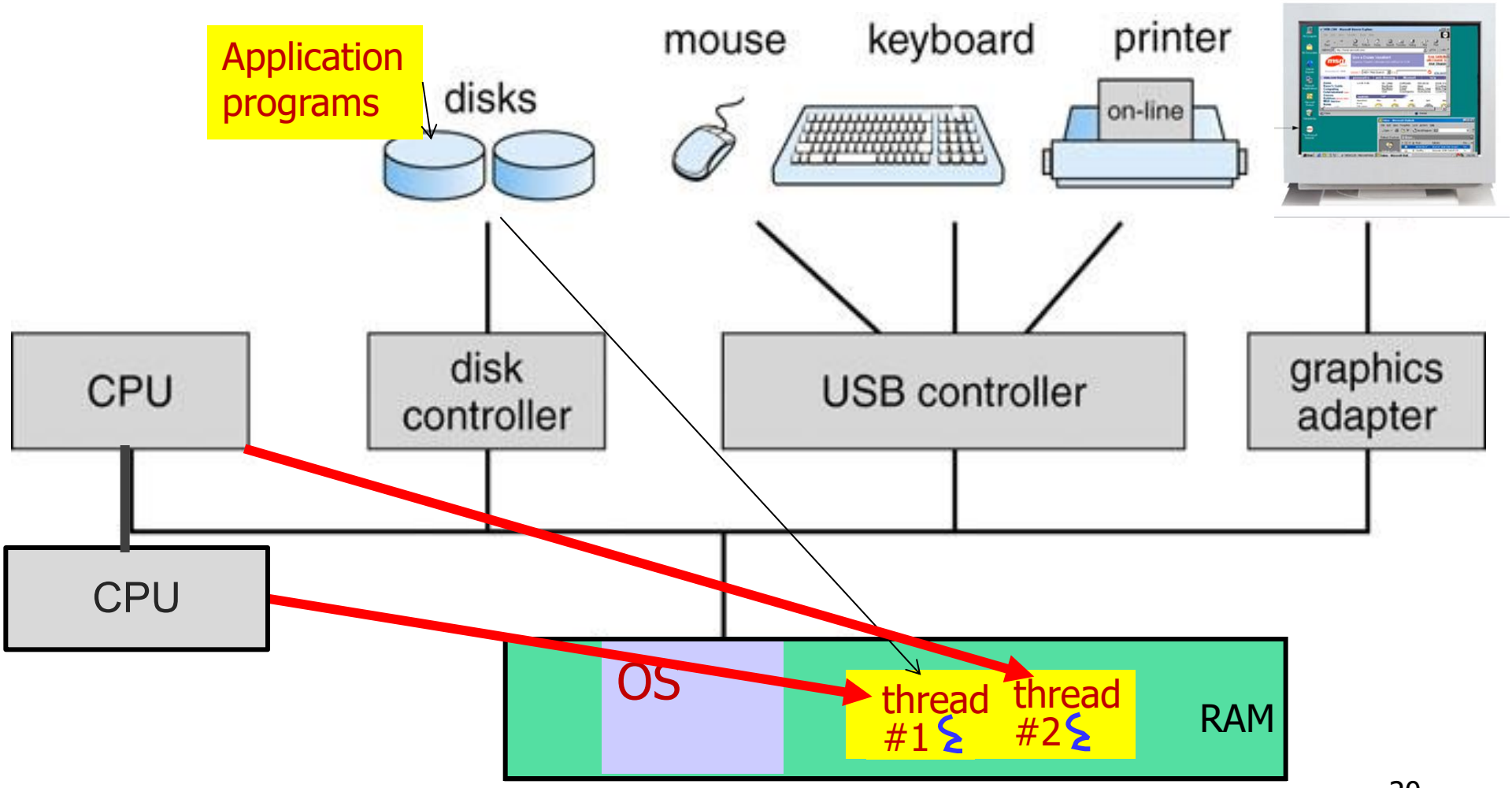
4.1.2 Benefits

- **The benefits of multithreaded programming:**
  - **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.
  - **Resource Sharing**
    - Threads share the memory and the resources of the process to which they belong.
  - **Economy**
    - More economical to create and context-switch threads.
  - **Scalability**
    - can take advantage of multiprocessor architectures, where threads may be running in parallel.

Increase Responsiveness

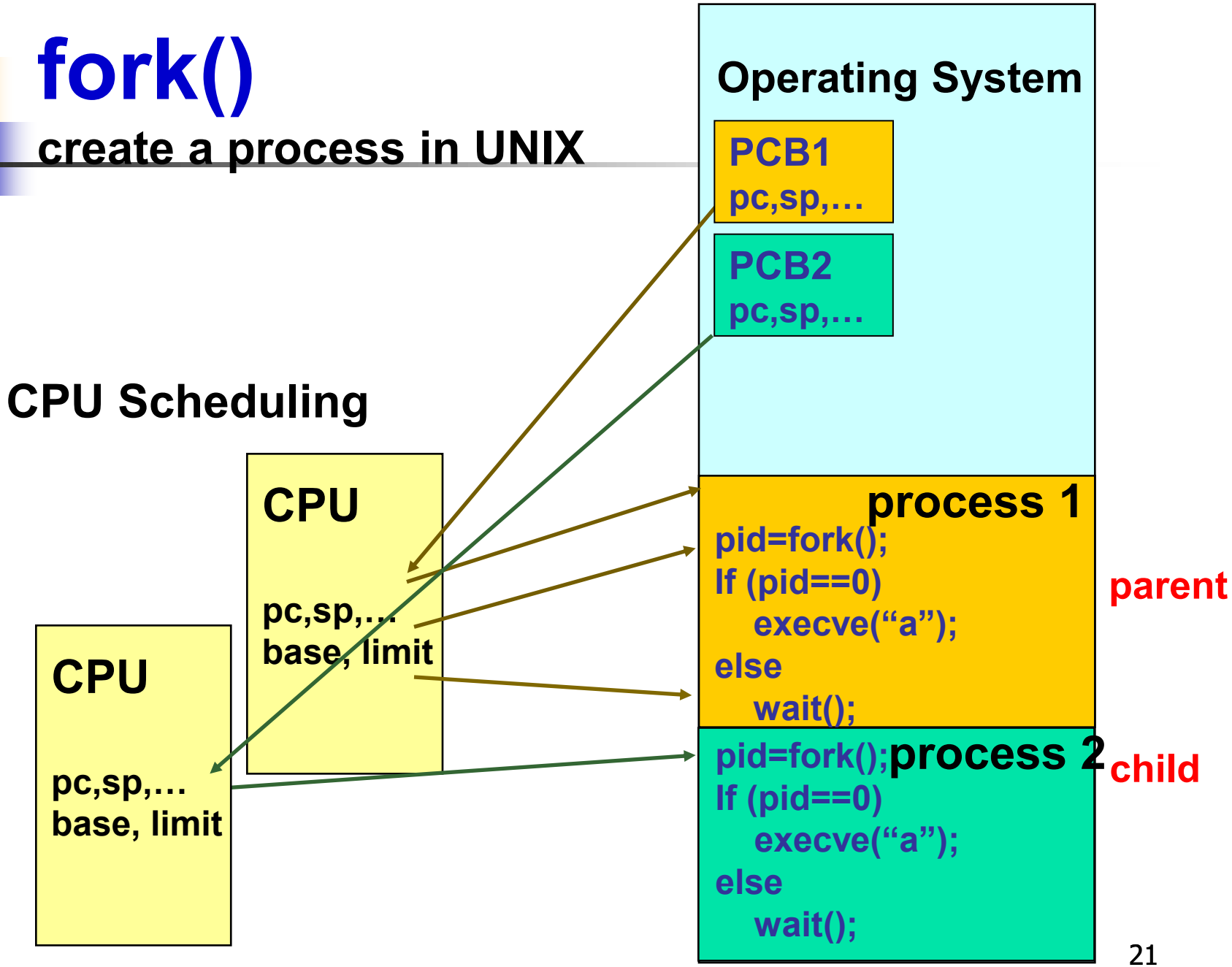


Parallel Execution



fork()

create a process in UNIX

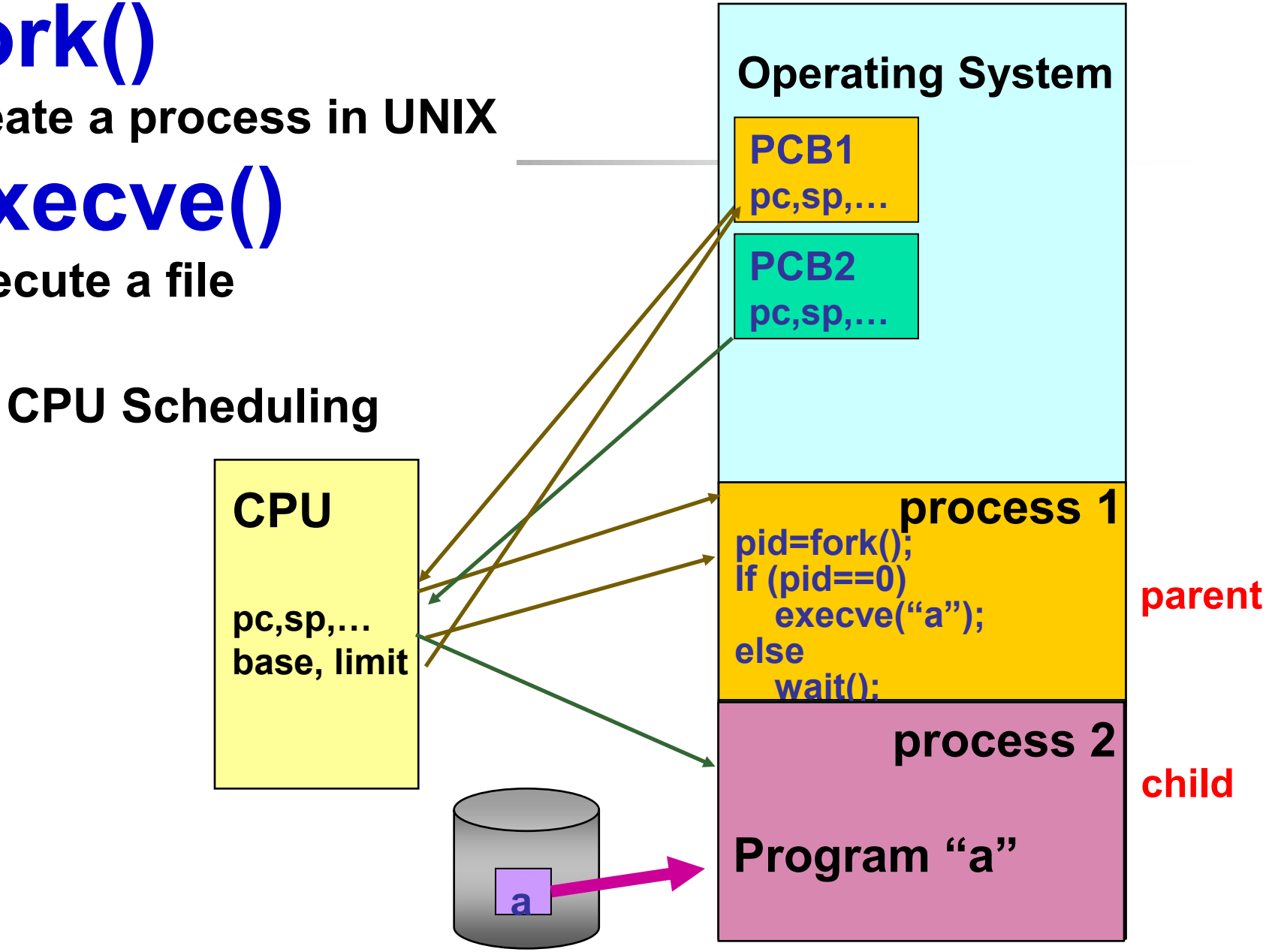


fork()

create a process in UNIX

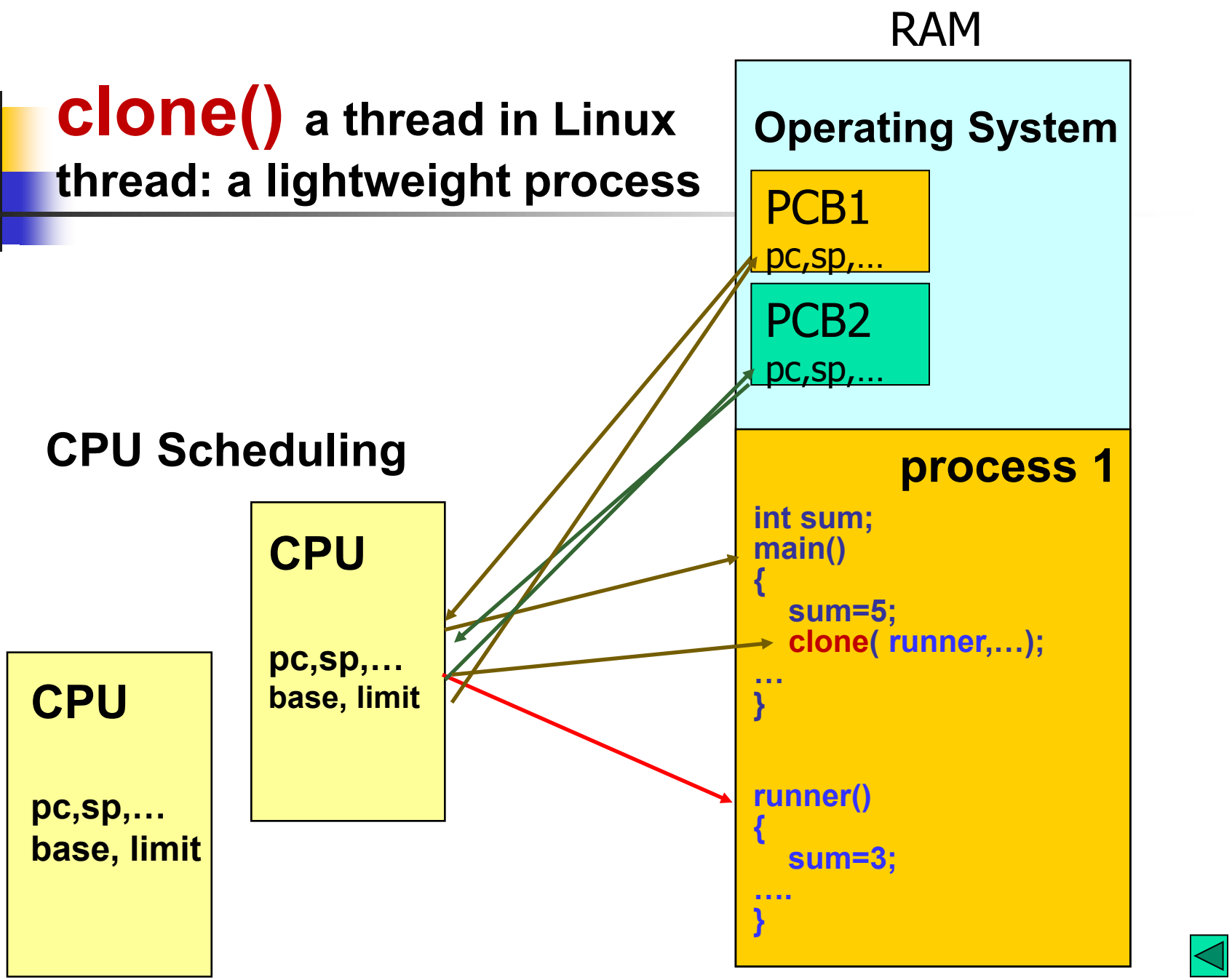
execve()

execute a file



clone() a thread in Linux

thread: a lightweight process



4.2 Multicore Programming

- **Multithreaded programming provides a mechanism for more efficient use of multiple computing cores and improved concurrency.**
- **On a system with a single computing core, concurrency merely means that the execution of the threads will be interleaved over time.**
- **Concurrent execution on single-core system:**

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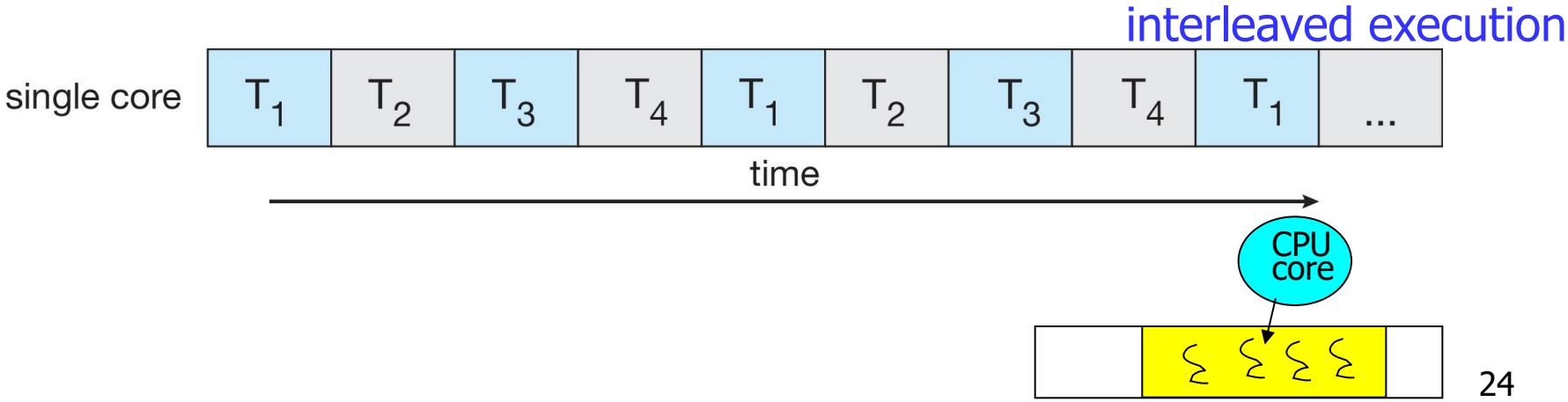
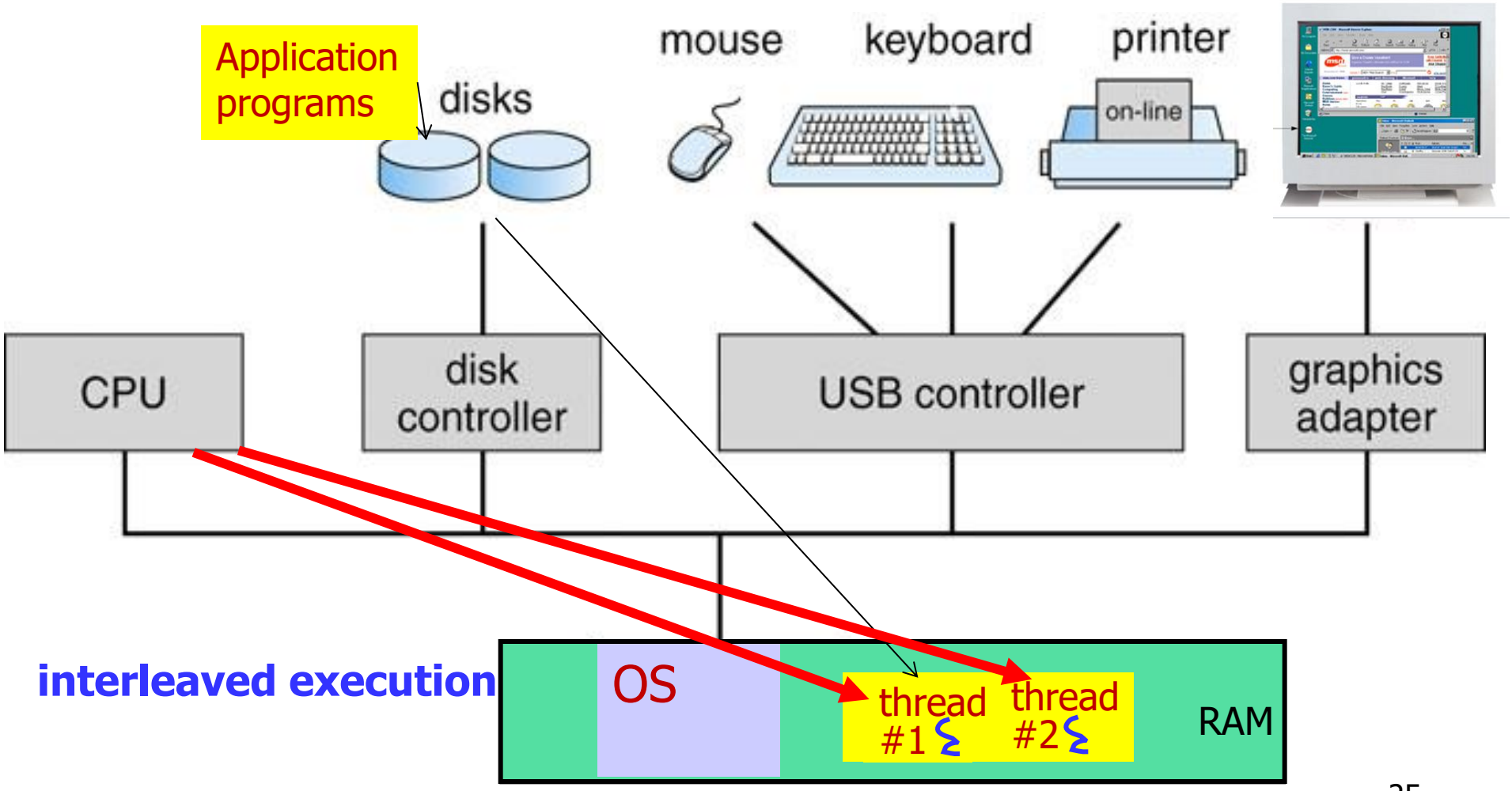


Concurrent Execution
on a Single-Core Processor



Multicore Programming (Cont.)

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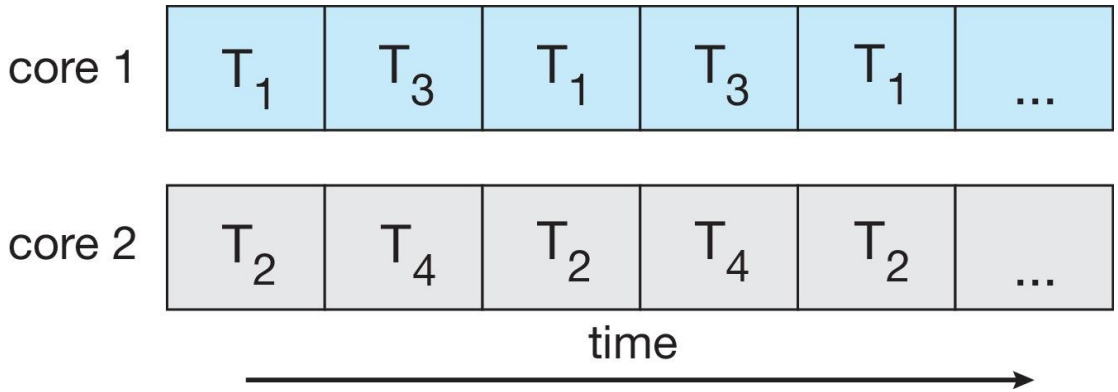
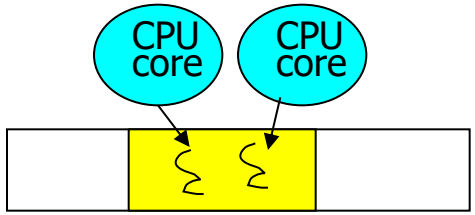
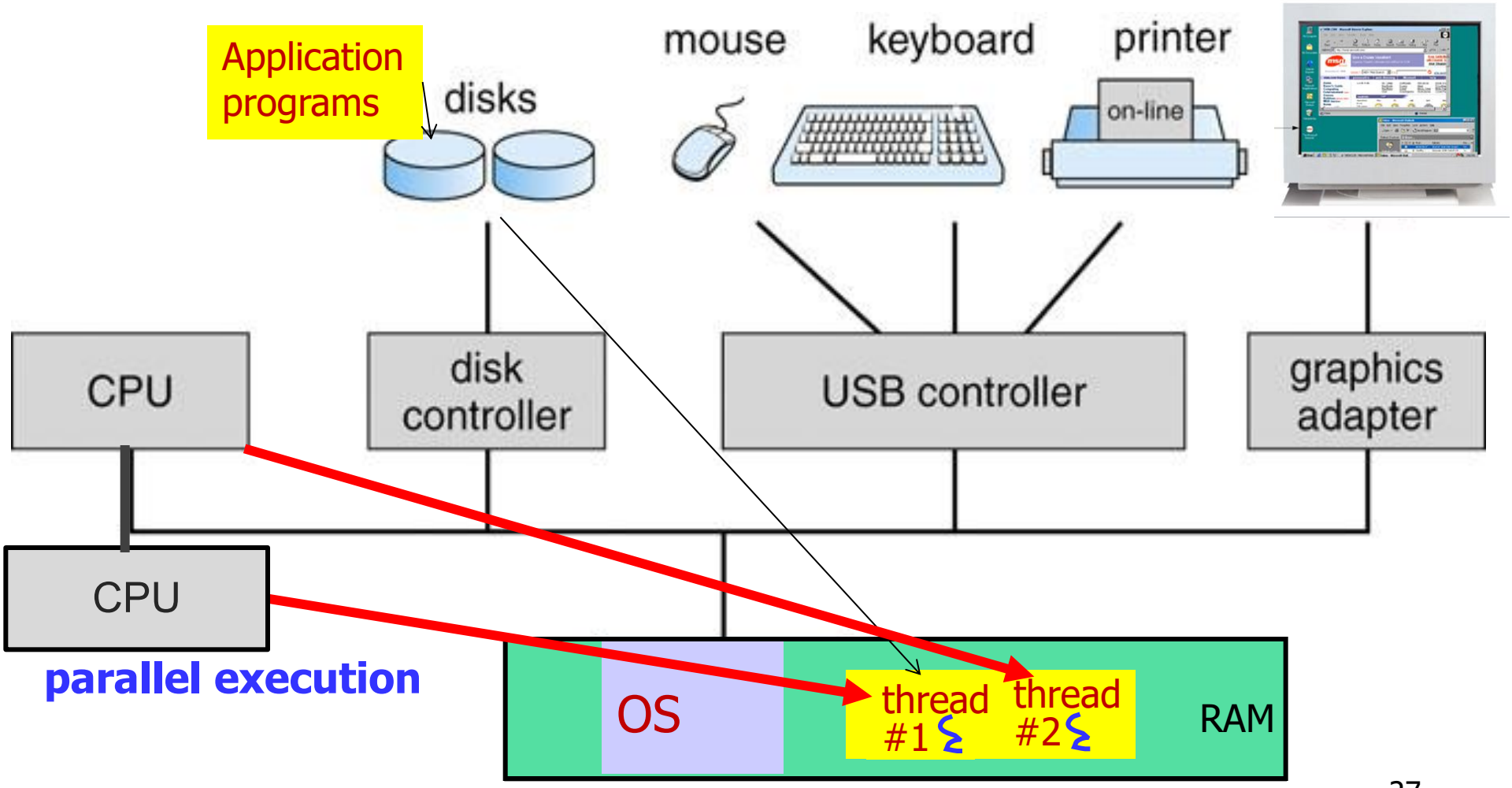
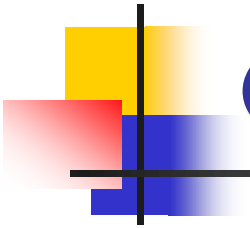
- On a system with multiple cores, **concurrency** means that the threads can run in parallel, as the system can assign a separate thread to each core.
- **Parallel** execution on a multi-core system:





Parallel Execution

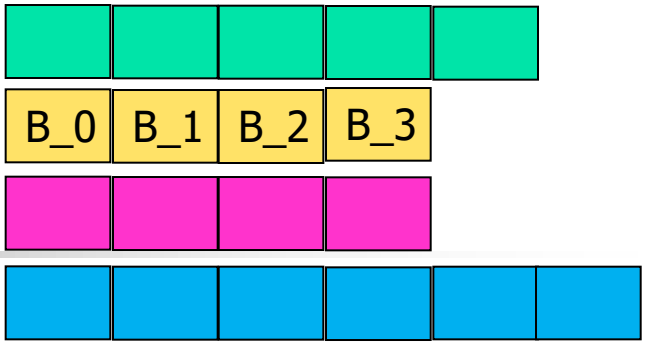


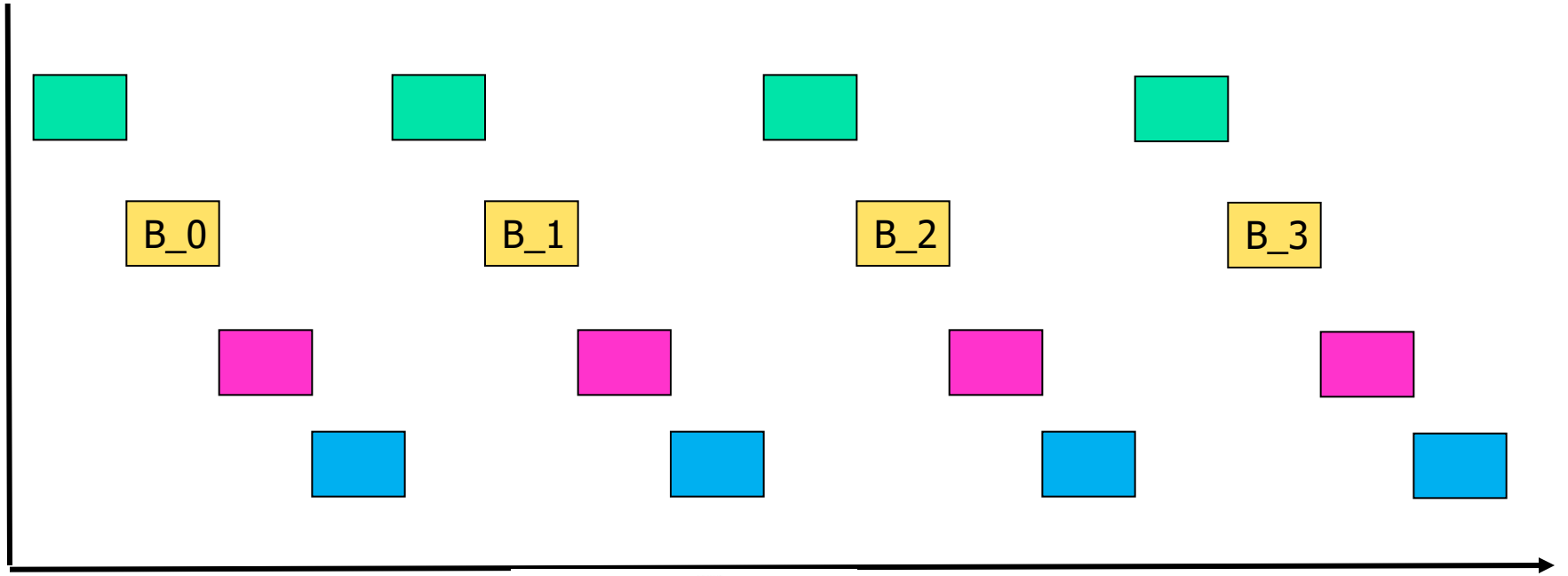


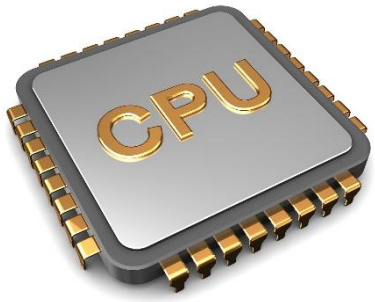
Concurrency vs. Parallelism

- **A system is *parall* if it can perform more than one task simultaneously**
- **A *concurrent* system supports more than one task by allowing all the tasks to make progress**
  - Single processor / core, CPU scheduler providing concurrency
    - Provide the illusion of parallelism by rapidly switching between processes, thereby allowing each process to make progress
    - Processes were running concurrently, but not in parallel

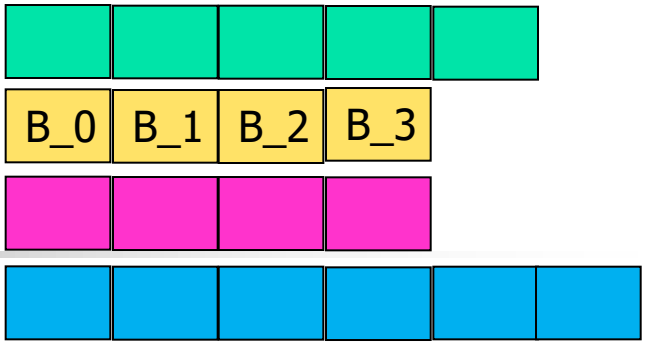
Concurrency

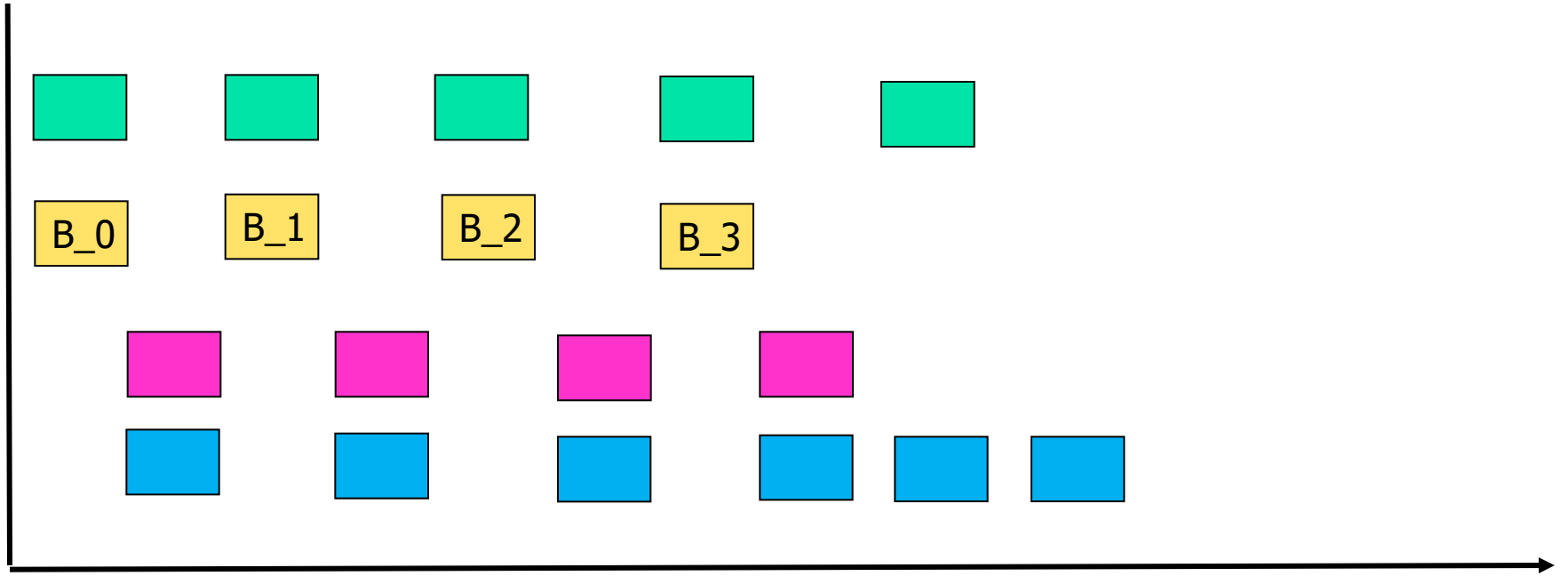


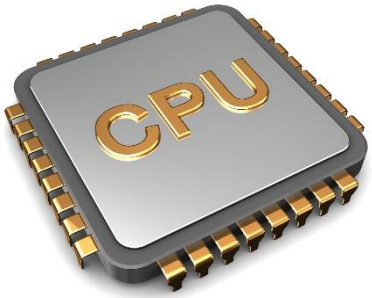


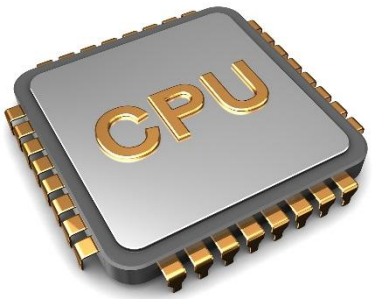


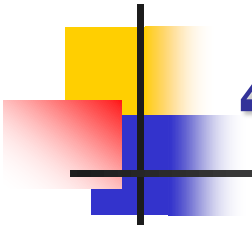
Concurrency







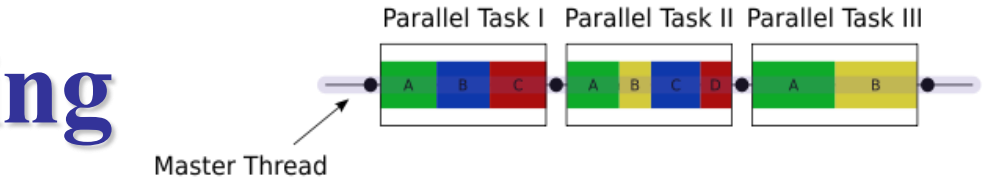


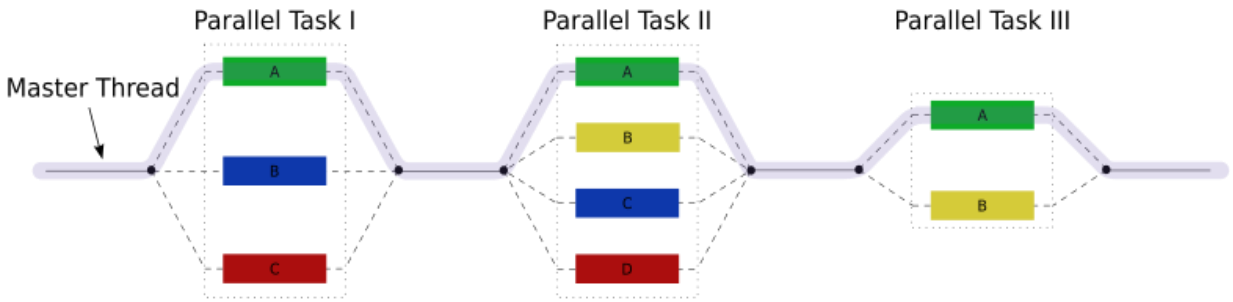


4.2.1 Programming Challenges

- **Multicore systems put pressure on system designers and application programmers to make better use of multiple computing cores.**
  - **OS designers**: write **scheduling algorithms** to allow the parallel execution on multiple processing cores
  - **Application programmers:** modify existing programs and design multithreaded programs

Programming Challenges (Cont.)

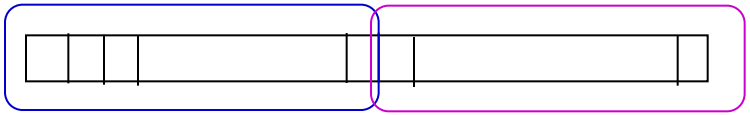




- **Challenges in programming for Multicore systems:**
  - **Dividing activities**
    - Identifying tasks that can run in parallel
  - **Balance**
    - Ensure that the tasks perform equal work
  - **Data splitting**
    - Data accessed by the tasks must be divided to run on separate cores
  - **Data dependency**
    - Ensure that the tasks' execution is synchronized to accommodate the data dependency
  - **Testing and debugging**

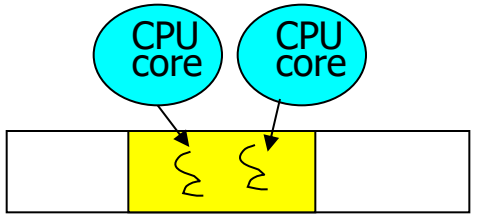
4.2.2 Types of Parallelism

- **Data parallelism – distributes subsets of the same data across multiple computing cores, perform the same operation on each core**
  - e.g., two threads sum array[N] on a dual-core system in parallel

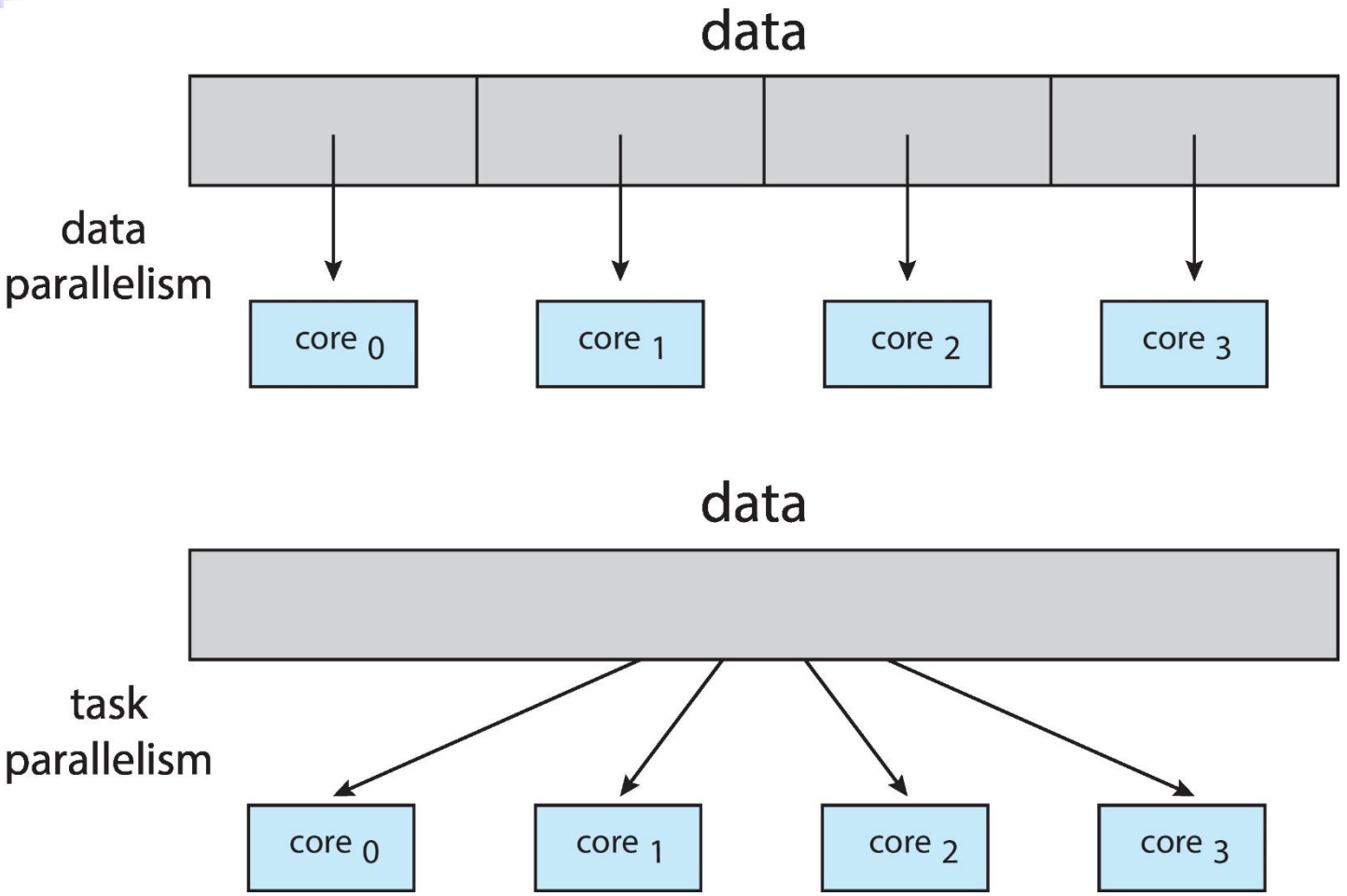


int array[N];

    - thread A sums array[0]..[N/2-1] on core 0
    - thread B sums array[N/2]..[N-1] on core 1
- **Task parallelism – distributing tasks (threads) across multiple computing cores, each thread is performing a unique operation**
  - e.g., thread A sums, thread B multiplies
  - e.g., producer thread, consumer thread



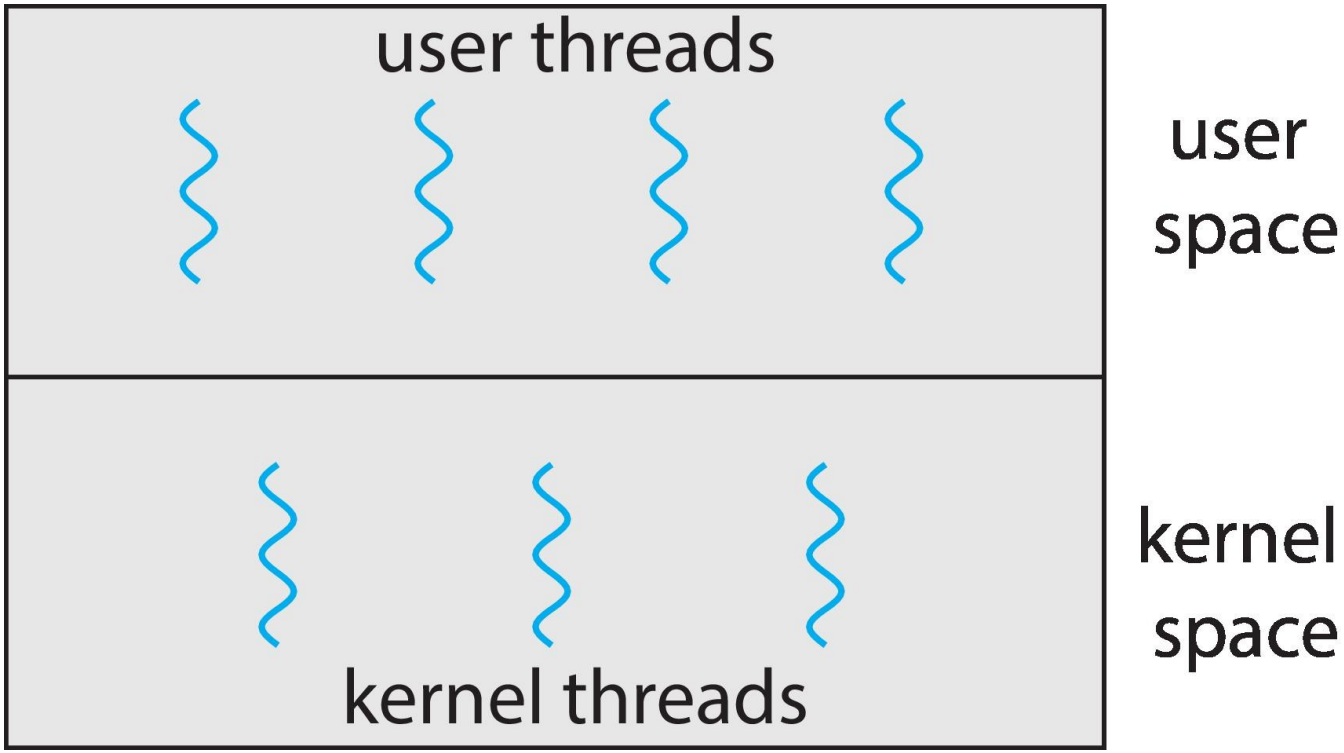
Data and task parallelism (Fig. 4.5)



4.3 Multithreading Models

- **Support for threads may be provided either at the user level, for user threads, or by the kernel, for kernel threads.**
- **User threads are supported above the kernel and are managed without kernel support, whereas kernel threads are supported and managed directly by the OS.**
- **Virtually all contemporary OSes support kernel threads:**
  - Windows, Linux, macOS

User and kernel threads (Fig. 4.6)



User-level Threads (1)

- **User-level threads are generally faster to create and manage than are kernel threads**
  - Because no intervention from the kernel is required

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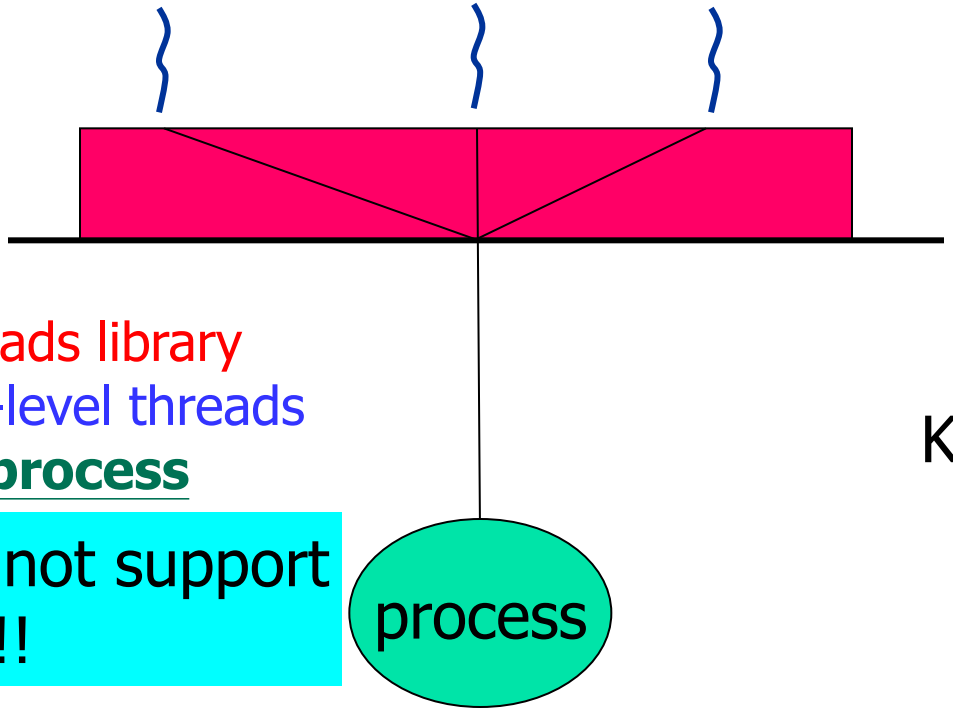
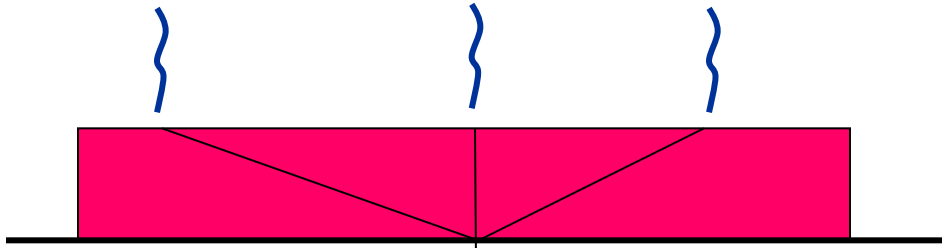


User-level threads library multiplex user-level threads above **an OS process**

If kernel does not support kernel thread!!!

User-level Threads (2)

- **User-level threads are generally faster to create and manage than are kernel threads**
  - Because no intervention from the kernel is required



Thread library

User space

User-level threads library multiplex user-level threads above an OS process

a kernel thread

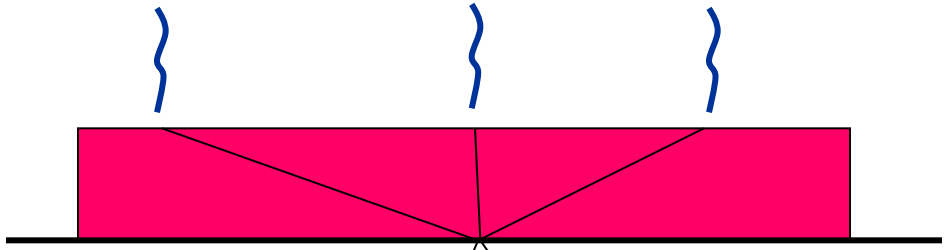
Kernel space

If kernel supports kernel thread!!!

kernel thread

User-level Threads (3)

- **User-level threads are generally faster to create and manage than are kernel threads**
  - Because no intervention from the kernel is required



Thread library

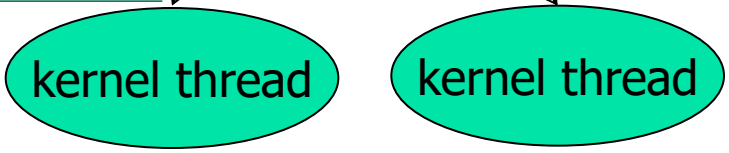
User space

User-level threads library multiplex user-level threads above an OS process

a kernel thread

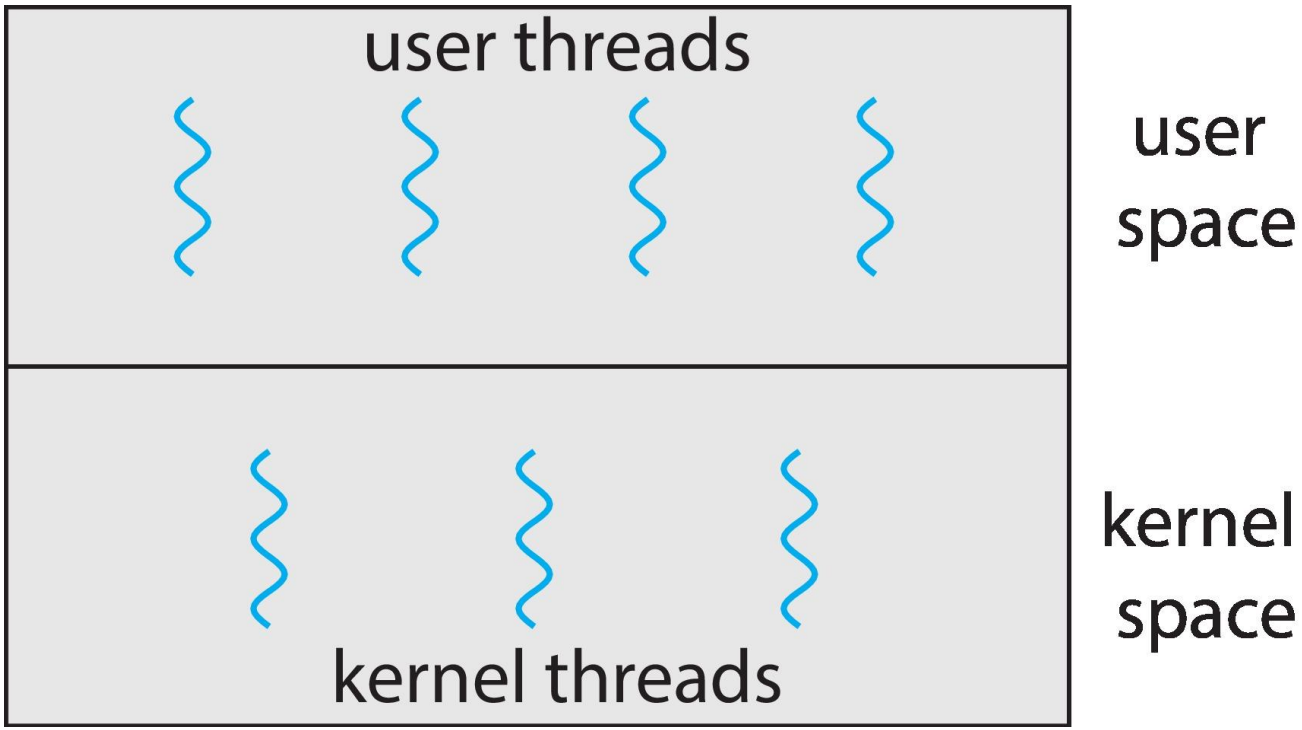
a set of kernel thread

Kernel space

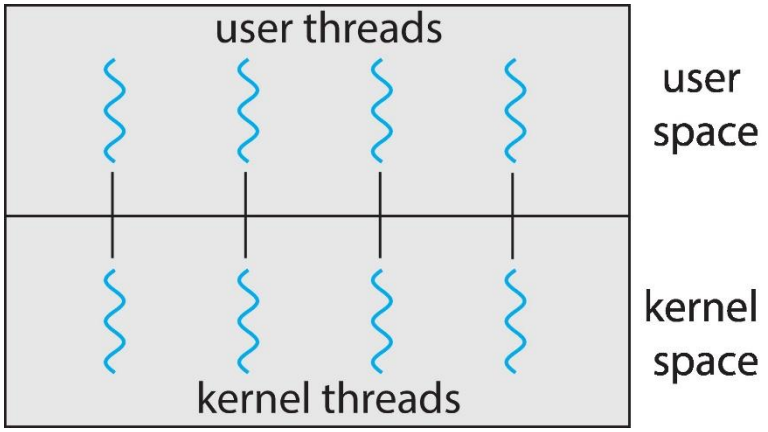


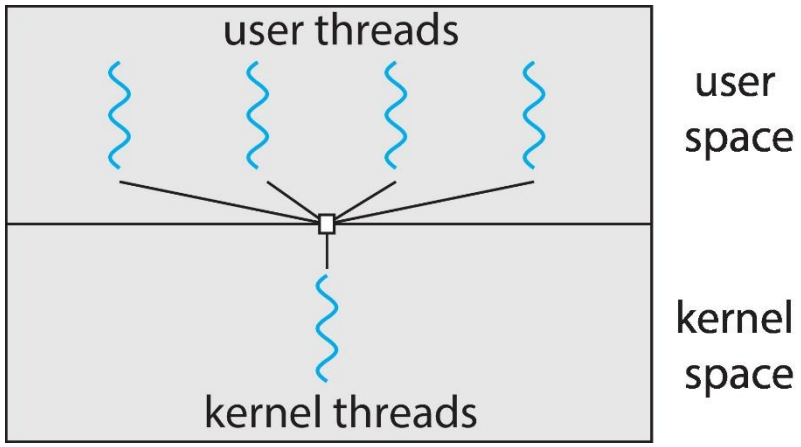
If kernel supports kernel thread!!!

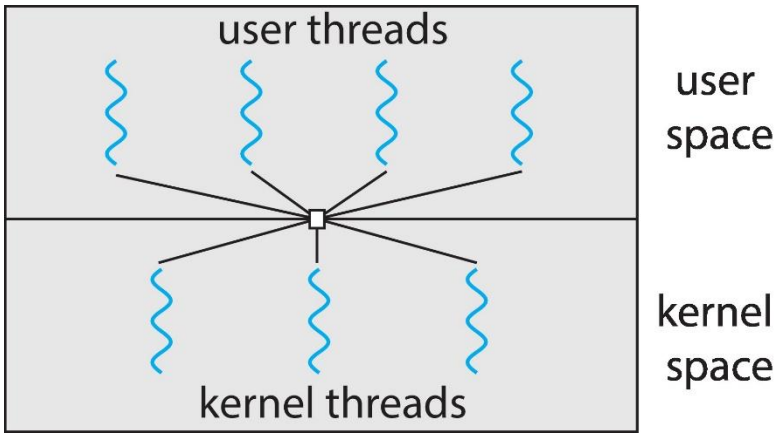
Relationship between user threads and kernel threads

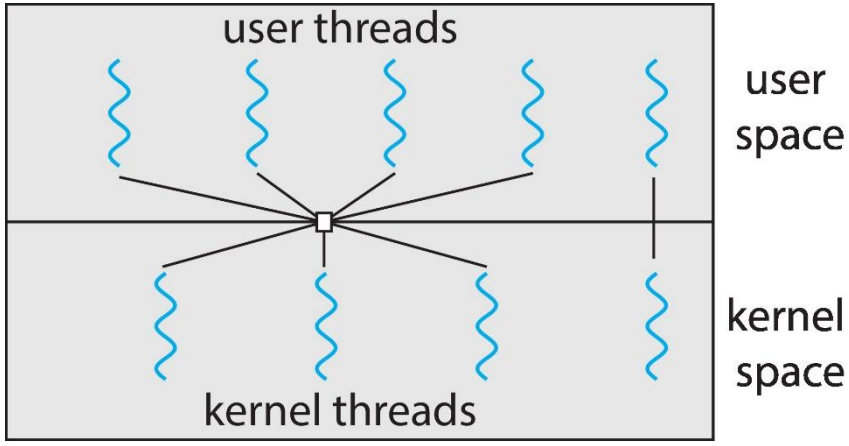


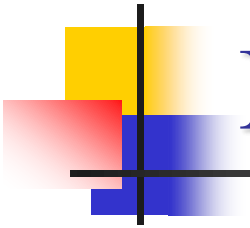
Relationship between user threads and kernel threads (Cont.)











Multithreading Models (Cont.)

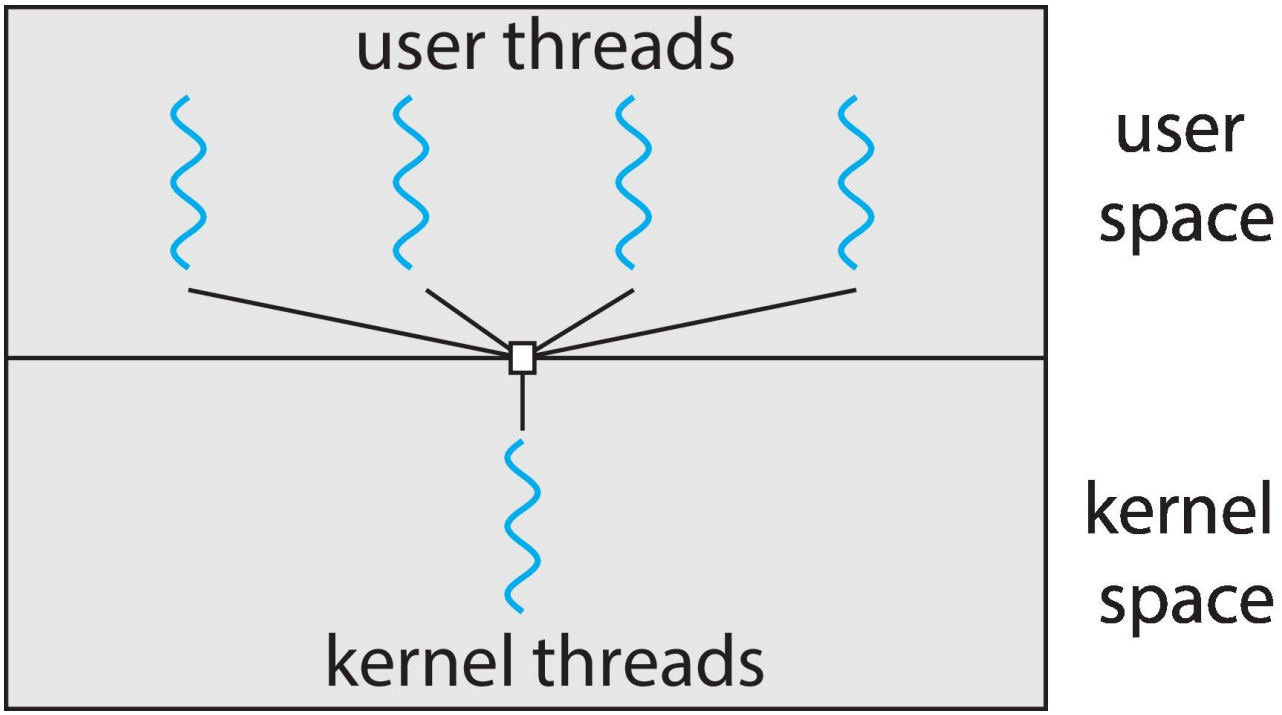
- Can threads run in parallel on multicore systems?
- If a thread makes a blocking system call, is the entire process still runnable?

Multithreading Models (Cont.)

- **Three common ways of establishing relationship between user threads and kernel threads:**
  - 4.3.1 Many-to-One Model 
  - 4.3.2 One-to-One Model 
  - 4.3.3 Many-to-Many Model 

4.3.1 Many-to-One Model

- **Maps many user-level threads to one kernel thread.**

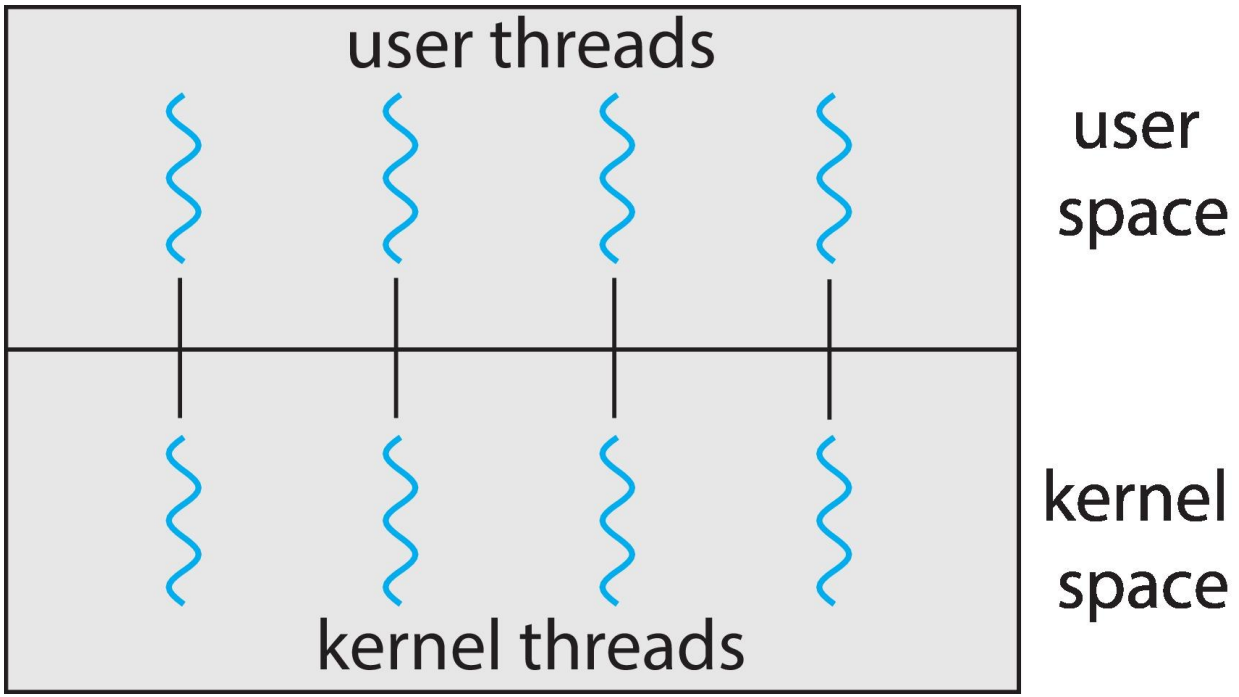


Many-to-One Model (Cont.)

- **Thread management is done by the thread library in user space, so it is efficient**
- **The entire process will block if a thread makes a blocking system call.**
  - because only one thread can access the kernel at a time
  - multiple threads are unable to run in parallel on multicore systems
- **Cannot take advantage of multiple processing cores**
    - very few systems currently use this model
- **Example:**
  - Green threads – a thread library for Solaris systems

4.3.2 One-to-One Model

- Maps each user thread to a kernel thread.



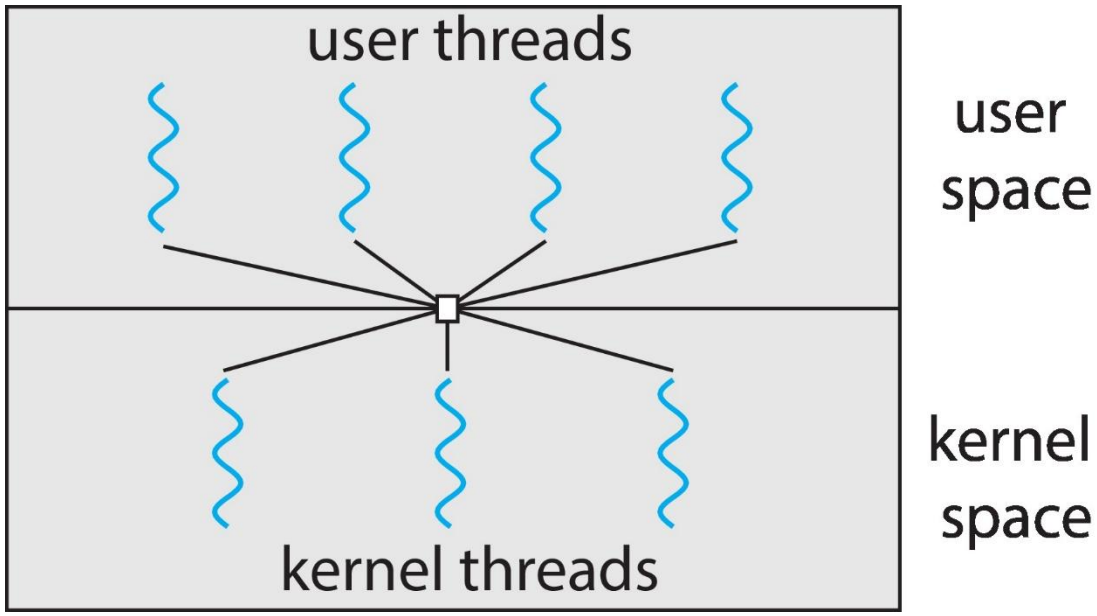
One-to-One Model (Cont.)

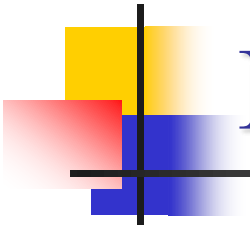
- **Provides more concurrency than many-to-one model by allowing another thread to run when a thread makes a blocking system call.**
- **Allows multiple threads to run in parallel on multiprocessors.**
- **Creating a user thread requires creating the corresponding kernel thread, and a large number of kernel threads may burden the performance of a system.**
- **Examples**
  - Linux, the family of Windows OSes

4.3.3 Many-to-Many Model

- **Multiplexes many user-level threads to a smaller or equal number of kernel threads.**

|user threads| >= |kernel threads|





Discussion of Concurrency

- **many-to-one model**
  - Allows the developer to create as many user threads as she wishes, it does not result in parallelism, because the kernel can schedule only one kernel thread at a time.
- **one-to-one model**
  - Allows greater concurrency, but the developer has to be careful not to create too many threads within an application.
  - When a thread performs a blocking system call, the kernel can schedule another thread for execution.
- **many-to-many model**
  - Developers can create as many user threads as necessary, and the corresponding kernel threads can run in parallel on a multiprocessor.
  - When a thread performs a blocking system call, the kernel can schedule another thread for execution.

Two-level Model

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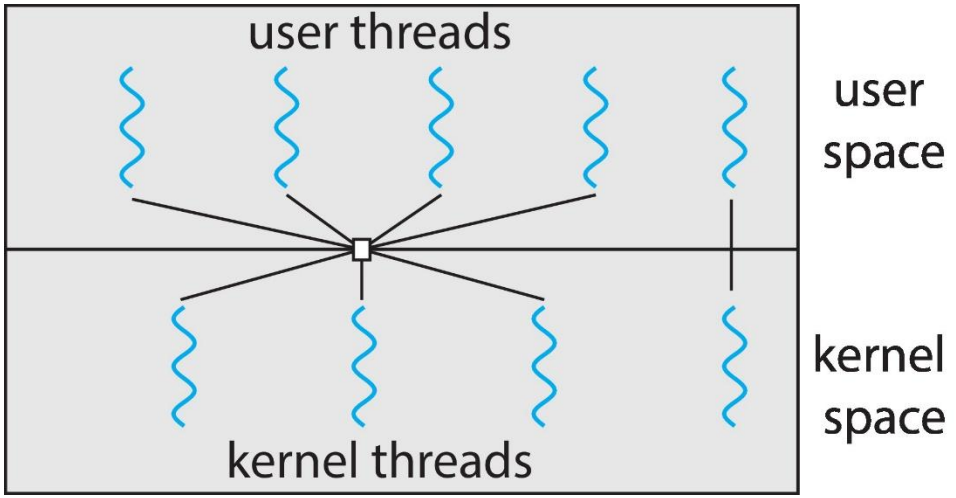
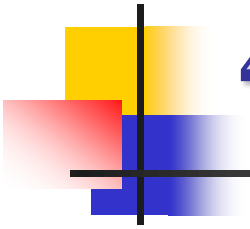
- **One variation on the many-to-many model**
  - still multiplexes many user-level thread to a smaller or equal number of kernel threads
  - also allows a user-level thread to be bound to a kernel thread
  - Appears to be the most flexible one, but is difficult to implement
- **With an increasing number of processing cores, limiting the number of kernel threads has become less important.**
  - Most OSes now use one-to-one model



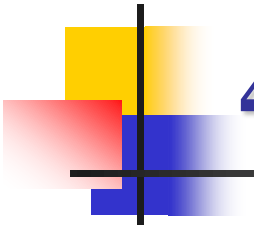


4.4 Thread Libraries

- **A thread library provides the programmer an API for creating and managing threads.**
- **Two primary ways of implementing a thread library:**
  - (1) Provide a library entirely in user space with no kernel support
    - All code and data structures for the library exist in user space.
      - Invoking a function in the library results in a local function call in user space and not a system call
  - (2) Implement a kernel-level library supported directly by OS
    - code and data structures for the library exist in kernel space.
      - Invoking a function in the API for the library results in a system call to the kernel

Thread Libraries (Cont.)

- **Three main thread libraries are in use today:**
  - (1) **POSIX Pthreads**
    - The threads extension of the POSIX standard, may be provided as either a user-level or kernel-level library.
  - (2) **Windows**
    - A kernel-level library available on Windows systems
  - (3) **Java**
    - The **Java thread API** allows thread creation and management directly in Java programs.
    - The Java thread API is typically implemented using a thread library available on the host system.
      - Windows API on Windows systems
      - Pthreads API on UNIX, Linux, macOS



4.4.1 Pthreads

- **Pthreads refers to the POSIX standard (IEEE 1003.1c) defining an 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-type systems:**
  - Linux, macOS

Multithreaded C program using the Pthread API (Fig. 4.11)

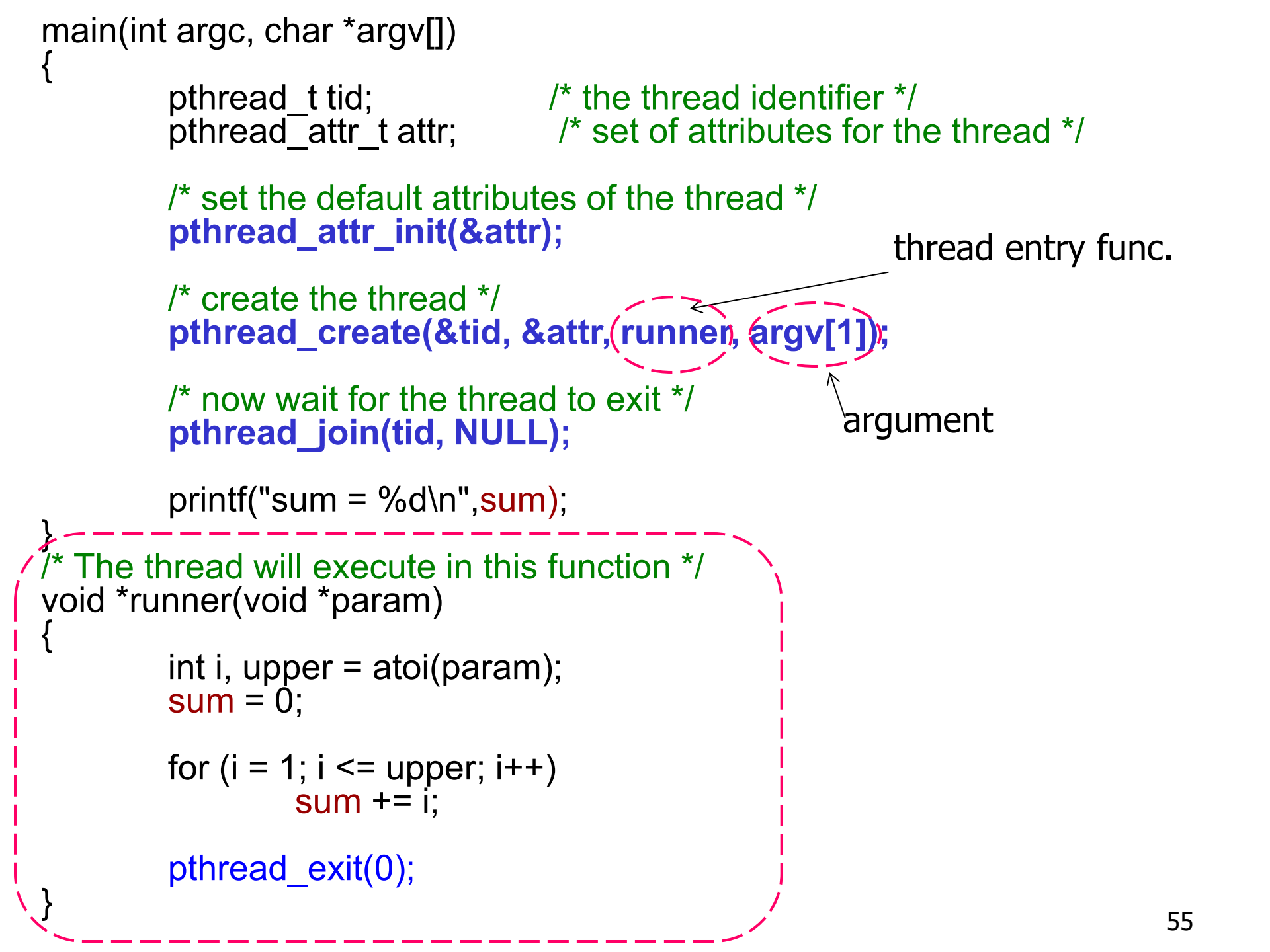
```
/**
 * A pthread program illustrating how to
 * create a simple thread and some of the pthread API
 * This program implements the summation function where
 * the summation operation is run as a separate thread.
 * Usage on Solaris/Linux/Mac OS X:
 *
 * gcc thrd.c -lpthread
 * a.out <number>
 */
```

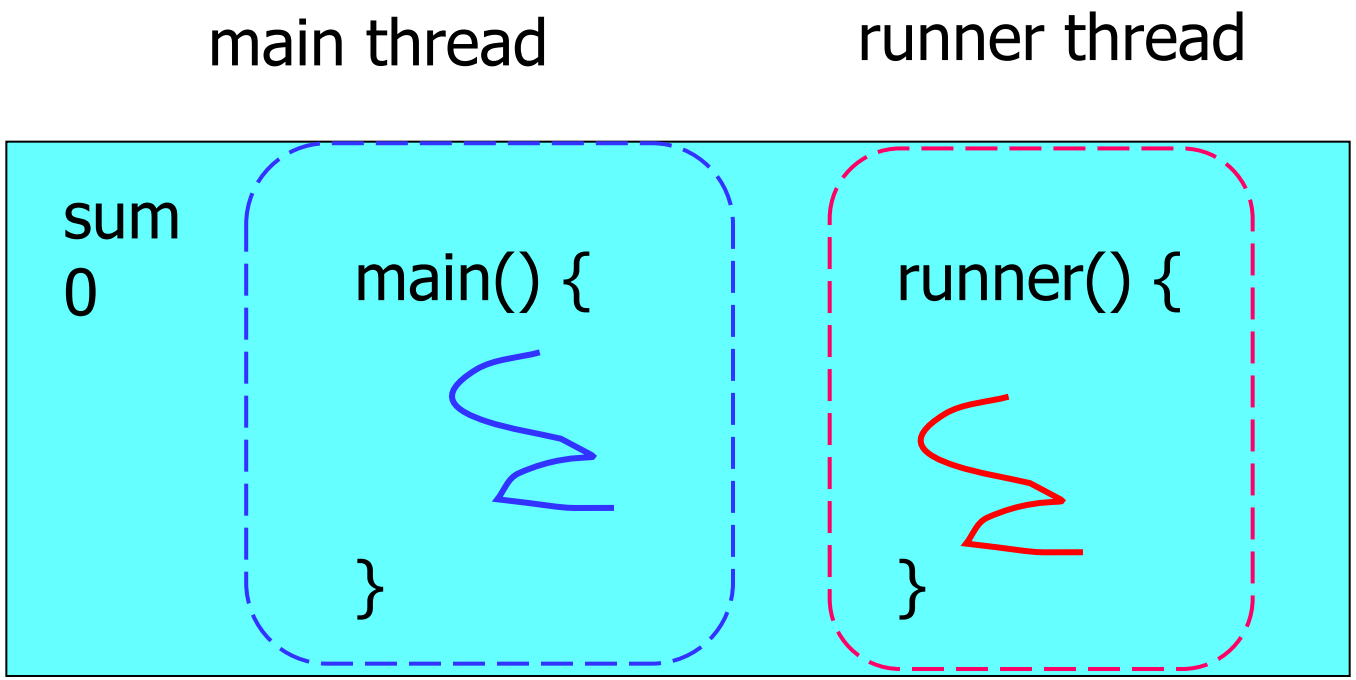
← compile & link with pthread lib.

$$sum = \sum_{i=1}^{N} i$$

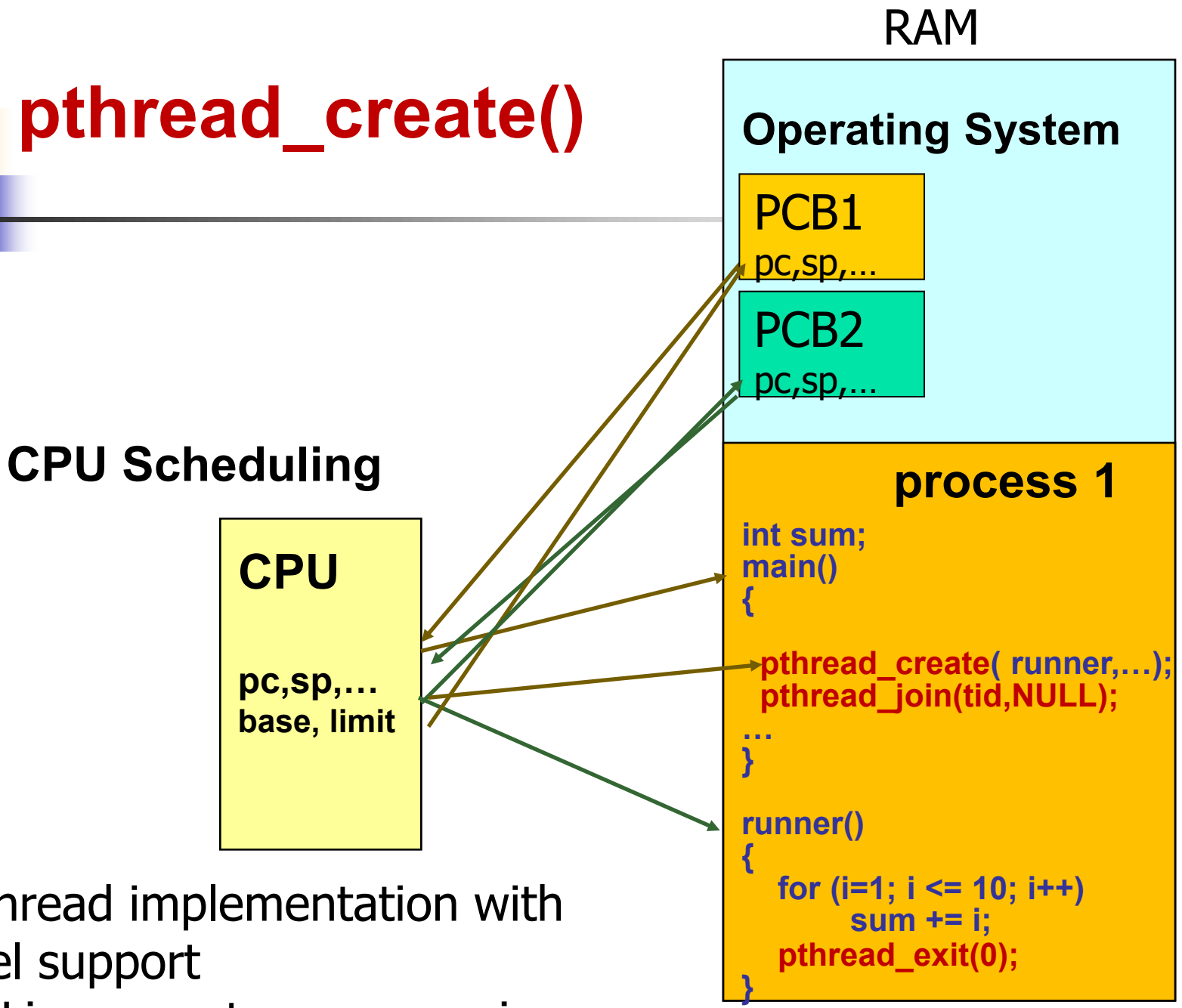
```
#include <pthread.h>
#include <stdio.h>

int sum; /* this data is shared by the thread(s) */

void *runner(void *param);          /* the thread */
```

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

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

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

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

        printf("sum = %d\n",sum);
}
/* 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 += i;

        pthread_exit(0);
}
```




main thread
runner thread
sum
0
main() {
}
runner() {
}

pthread_create()

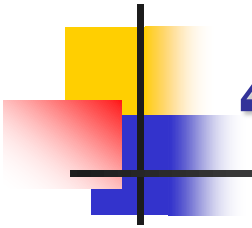


* if thread implementation with kernel support
e.g., Linux one-to-one mapping

Pthreads Code for Joining 10 Threads (Fig. 4.12)

```
#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);
```

Figure 4.12 Pthread code for joining ten threads.



4.4.2 Windows Threads

- The technique for creating threads using the Windows thread library is similar to the Pthreads technique.
- Figure 4.13: Multithreaded C program using the Windows API.

Multithreaded C program using the Windows API (Fig. 4.13)

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

DWORD Sum; /* data is shared by the thread(s) */

/* the thread runs in this separate function */
DWORD WINAPI Summation(LPVOID Param)
{
        DWORD Upper = *(DWORD *)Param;

        for (DWORD i = 0; i <= Upper; i++)
                Sum += i;
        return 0;
}
```

$$sum = \sum_{i=0}^{N} i$$

Multithreaded C program using Win32 API (Fig. 4.13) (Cont.)

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

        Param = atoi(argv[1]);
        // create the thread
        ThreadHandle = CreateThread(NULL, 0, Summation,
                                    &Param, 0, &ThreadId);

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

        // close the thread handle
        CloseHandle(ThreadHandle);

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


4.4.3 Java Threads

- **Java provides support at the language level for the creation and management of threads.**
- **Java threads are managed by Java Virtual Machine.**
- **Typically implemented using the threads model provided by underlying OS**
- **Java threads may be created by:**
  - (1) Extending Thread class
  - (2) Defining a class that implements the Runnable interface

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

Standard practice is to implement Runnable interface

(1) Java program for the summation of a non-negative integer

```
public class Summation extends Thread
{
        public Summation(int n) {
                upper = n;
        }

        public void run() {
                int sum = 0;

                if (upper > 0) {
                        for (int i = 1; i <= upper; i++)
                                sum += i;
                }

                System.out.println("The summation of " + upper + " is " + sum);
        }

        private int upper;
}
```

$$sum = \sum_{i=0}^{N} i$$

(1) Java program for the summation of a non-negative integer (Cont.)

```
public class ThreadTester
{
    public static void main(String[] args) {
        if (args.length > 0) {
            if (Integer.parseInt(args[0]) < 0)
                throw new IllegalArgumentException(args[0] + "
    must be non-negative.");
            else {
                Summation summationThread = new
                    Summation(Integer.parseInt(args[0]));
                summationThread.start();
            }
        }
        else
            System.err.println("Usage: Summation <integer value>");
    }
}
```


(2) Java program for the summation of a non-negative integer (Fig. 4.12)

```
/**
 * This program creates a separate thread by implementing the Runnable interface.
  * To compile, enter
 *  javac Driver.java
*/
class Sum
{
    private int sum;
    public int getSum() {
        return sum;
    }
    public void setSum(int sum) {
        this.sum = sum;
    }
}
```

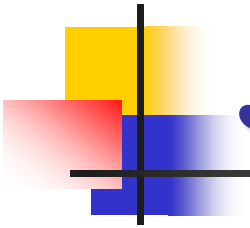
(2) Java program for the summation of a non-negative integer (Cont.)

```
class Summation implements Runnable
{
    private int upper;
    private Sum sumValue;

    public Summation(int upper, Sum sumValue) {
        if (upper < 0)
            throw new IllegalArgumentException();
        this.upper = upper;
        this.sumValue = sumValue;
    }

    public void run() {
        int sum = 0;

        for (int i = 0; i <= upper; i++)
            sum += i;
        sumValue.setSum(sum);
    }
}
```

$$sum = \sum_{i=0}^{N} i$$

(2) Java program for the summation of a non-negative integer(Cont.)

```
public class Driver
{
    public static void main(String[] args) {
        if (args.length != 1) {
            System.err.println("Usage Driver <integer>");
            System.exit(0);
        }

        // create the object to be shared
        Sum sumObject = new Sum();
        int upper = Integer.parseInt(args[0]);

        Thread thrd = new Thread(new Summation(upper, sumObject));
        thrd.start();
        try {
            thrd.join();
        } catch (InterruptedException ie) { }
        System.out.println("The sum of " + upper + " is " + sumObject.get());
    }
}
```



Java Threads

Implementing Runnable interface:

```
class Task implements Runnable
{
   public void run() {
      System.out.println("I am a thread.");
   }
}
```

Creating a thread:

```
Thread worker = new Thread(new Task());
worker.start();
```

Waiting on a thread:

```
try {
   worker.join();
}
catch (InterruptedException ie) { }
```

Java Executor Framework

- **Rather than explicitly creating threads, Java also allows thread creation around the Executor interface:**

```
public interface Executor
{
   void execute(Runnable command);
}
```

The Executor is used as follows:

```
Executor service = new Executor;
service.execute(new Task());
```

Java Executor Framework

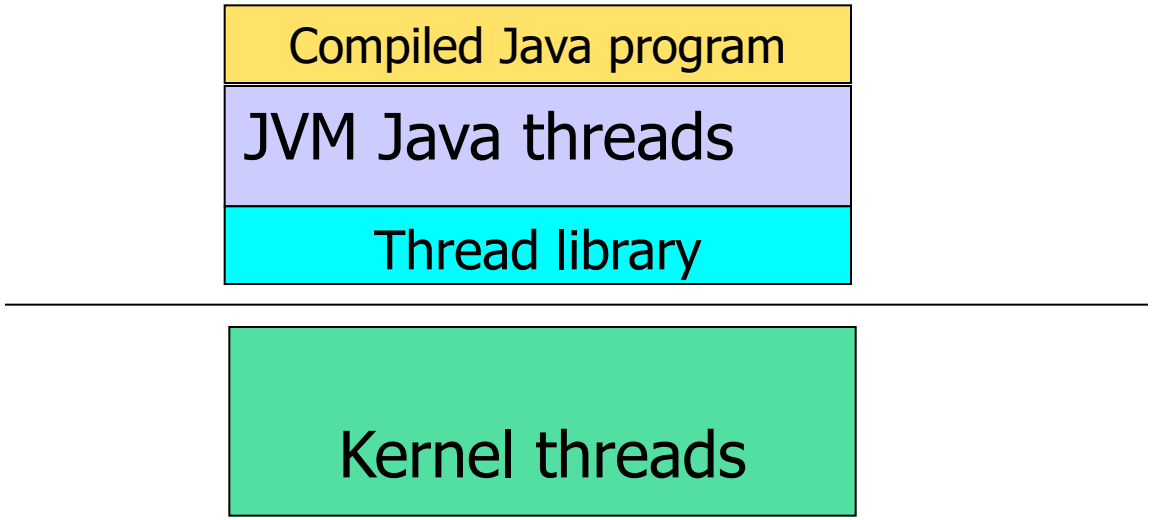
```
import java.util.concurrent.*;

class Summation implements Callable<Integer>
{
   private int upper;
   public Summation(int upper) {
      this.upper = upper;
   }

   /* The thread will execute in this method */
   public Integer call() {
      int sum = 0;
      for (int i = 1; i <= upper; i++)
         sum += i;

      return new Integer(sum);
   }
}
```

Java Executor Framework (cont.)

```
public class Driver
{
 public static void main(String[] args) {
    int upper = Integer.parseInt(args[0]);

    ExecutorService pool = Executors.newSingleThreadExecutor();
    Future<Integer> result = pool.submit(new Summation(upper));

    try {
        System.out.println("sum = " + result.get());
    } catch (InterruptedException | ExecutionException ie) { }
  }
}
```

Java Threads (Cont.)

- The specification for the JVM does not indicate how Java threads are to be mapped to the underlying OS, instead leaving that decision to the particular implementation of JVM.



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4.5 Implicit Threading

- **Growing in popularity as numbers of threads increase, program correctness more difficult with explicit threads**
- **Creation and management of threads done by compilers and run-time libraries rather than programmers**
- **Five methods explored**
  - Thread Pools
  - Fork-Join
  - OpenMP
  - Grand Central Dispatch
  - Intel Threading Building Blocks

4.5.1 Thread pools

- ***a multithreaded server***
  - Whenever the server receives a request, it creates a separate thread to service the request.
  - Potential problems:
    - thread creation time, unlimited threads could exhaust system resources
- ***Thread pools***
  - Create a number of threads at process startup and place them into a pool, where they sit and wait for work.
  - When a server receives a request, it awakens a thread from this pool, passing it the request for service.
  - Once the thread completes its service, it returns to the pool awaiting more work.

Thread pools (Cont.)

- **Benefits of thread pools**
  - Faster to service a request with an existing thread than waiting to create a thread
  - Limits the number of threads that exist at any one point.
  - Separating task to be performed from mechanics of creating task allows different strategies for running task
    - i.e. tasks could be scheduled to run periodically
- **Examples:**
  - Windows thread pool API

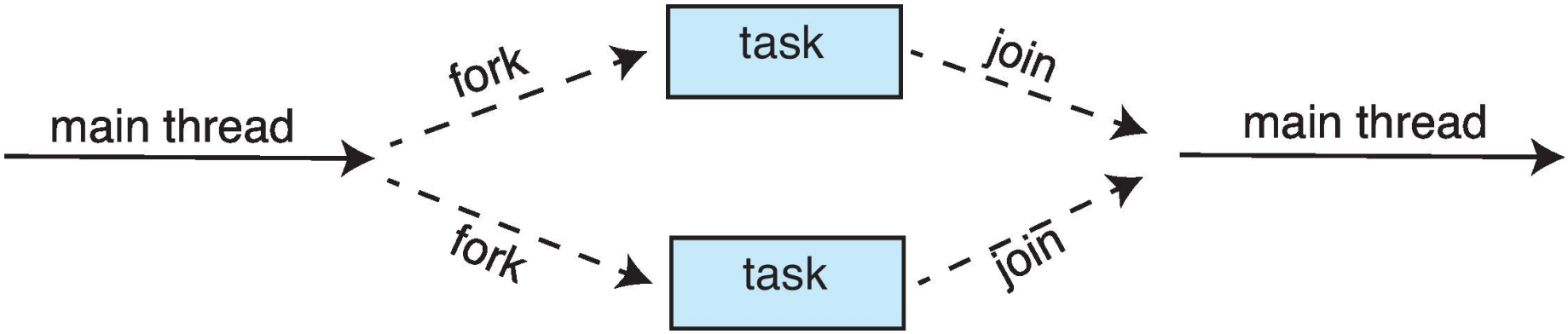
```
DWORD WINAPI PoolFunction(AVOID Param) {
    /*
    * this function runs as a separate thread.
    */
}

QueueUserWorkItem(&PoolFunction, NULL, 0);
```

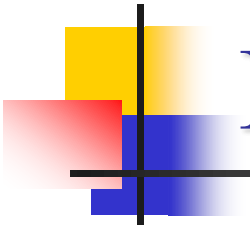
  - Java provides a thread pool utility

4.5.2 Fork Join

Fork-Join Parallelism

- **Multiple threads (tasks) are forked, and then joined.**



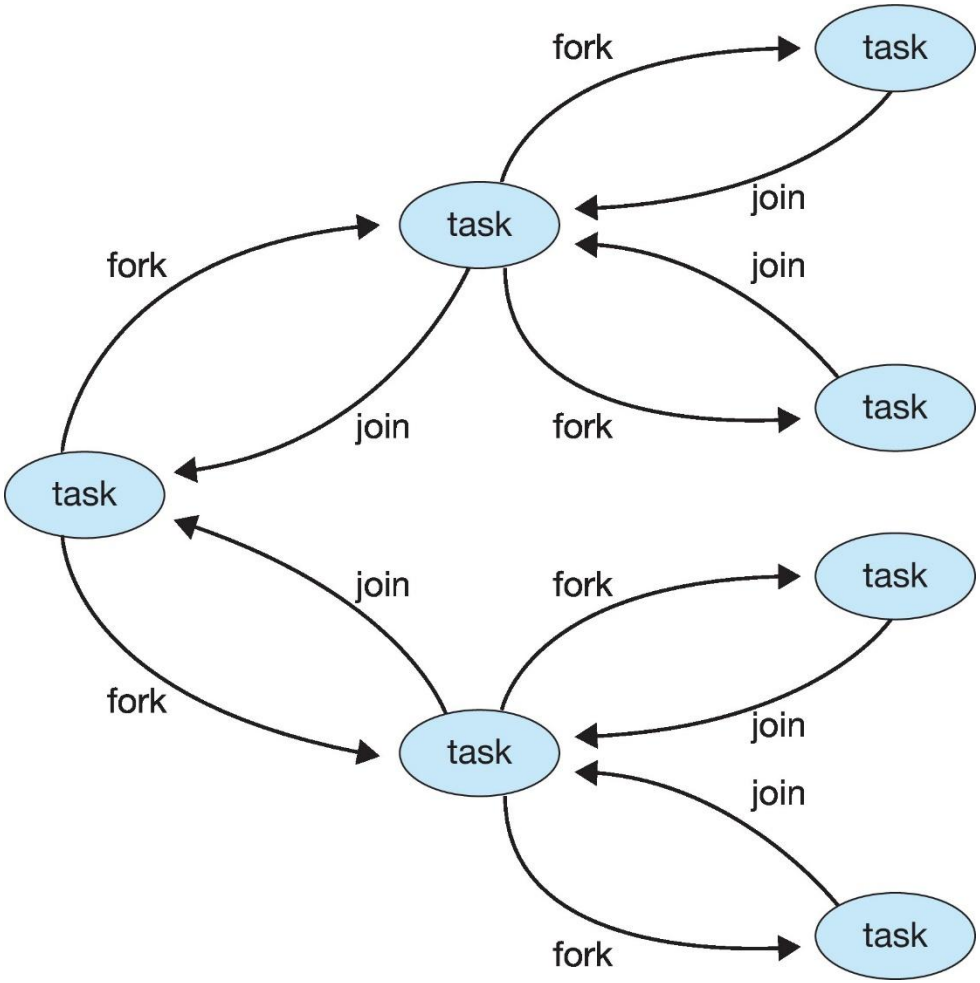


Fork-Join Parallelism

- **General algorithm for fork-join strategy:**

```
Task(problem)
   if problem is small enough
      solve the problem directly
   else
      subtask1 = fork(new Task(subset of problem)
      subtask2 = fork(new Task(subset of problem)

      result1 = join(subtask1)
      result2 = join(subtask2)

      return combined results
```

Fork-Join Parallelism



Fork-Join Parallelism in Java

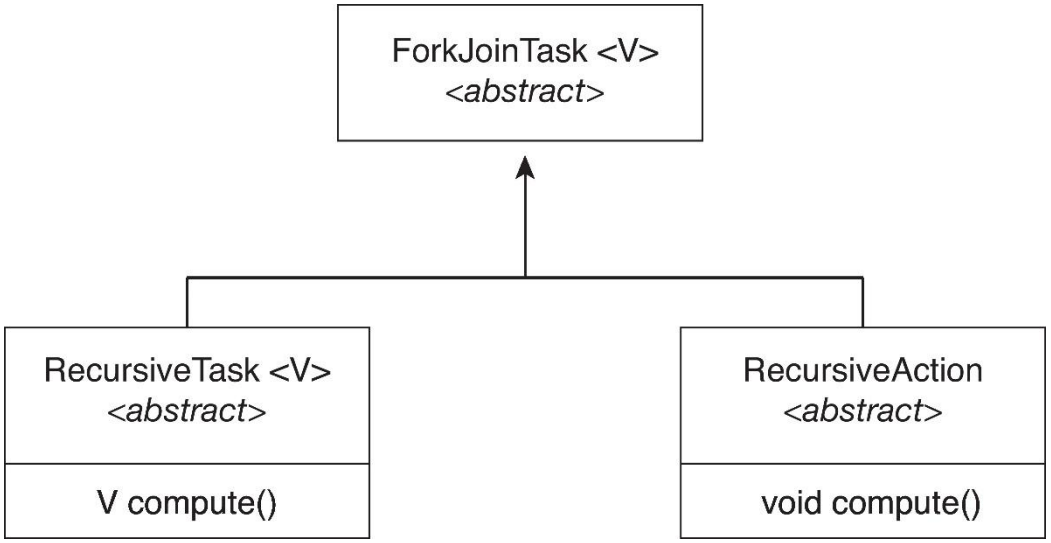
```
ForkJoinPool pool = new ForkJoinPool();
// array contains the integers to be summed
int[] array = new int[SIZE];

SumTask task = new SumTask(0, SIZE - 1, array);
int sum = pool.invoke(task);
```

Fork-Join Parallelism in Java

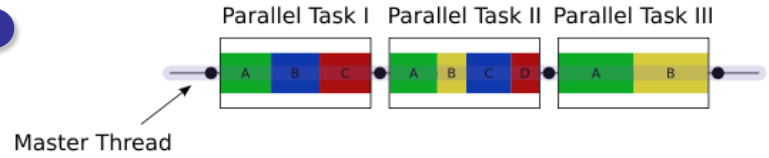
```
import java.util.concurrent.*;

public class SumTask extends RecursiveTask<Integer>
{
   static final int THRESHOLD = 1000;

   private int begin;
   private int end;
   private int[] array;

   public SumTask(int begin, int end, int[] array) {
      this.begin = begin;
      this.end = end;
      this.array = array;
   }

   protected Integer compute() {
      if (end - begin < THRESHOLD) {
         int sum = 0;
         for (int i = begin; i <= end; i++)
            sum += array[i];

         return sum;
      }
      else {
         int mid = (begin + end) / 2;

         SumTask leftTask = new SumTask(begin, mid, array);
         SumTask rightTask = new SumTask(mid + 1, end, array);

         leftTask.fork();
         rightTask.fork();

         return rightTask.join() + leftTask.join();
      }
   }
}
```

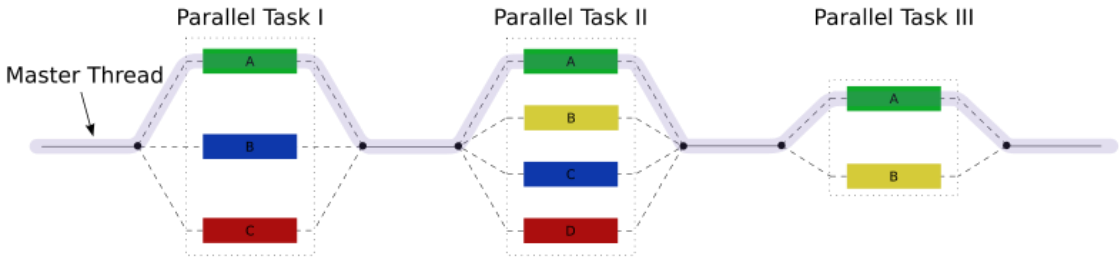
Fork-Join Parallelism in Java

- The ForkJoinTask is an abstract base class
- RecursiveTask and RecursiveAction classes extend ForkJoinTask
- RecursiveTask returns a result (via the return value from the compute() method)
- RecursiveAction does not return a result



4.5.3 OpenMP





- A 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 may run in parallel
- OpenMP is available on several open-source and commercial compilers for Linux, Windows, and Mac OS X systems.

OpenMP (Cont.)

#pragma omp parallel

Create as many threads as there are cores

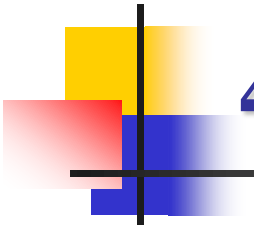
#pragma omp parallel for

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

Run for loop 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;
}
```

4.5.4 Grand Central Dispatch



- **A technology for Apple Mac OS X and iOS**
- **Extensions to C, C++ languages, API, and run-time library**
- **Allows application developers to identify parallel sections**
- **Manages most of the details of threading**
- **Block is in "^{}" -** `^{ printf("I am a block"); }`
- **Blocks placed in dispatch queue**
  - Assigned to available thread in thread pool when removed from queue

Grand Central Dispatch (Cont.)

- **Two types of dispatch queues:**
  - serial – blocks removed in FIFO order, queue is per process, called **main queue**
    - Programmers can create additional serial queues within program
  - concurrent – removed in FIFO order but several may be removed at a time
    - Three system wide queues with priorities low, default, high

```
dispatch_queue_t queue = dispatch_get_global_queue
   (DISPATCH_QUEUE_PRIORITY_DEFAULT, 0);

dispatch_async(queue, ^{ printf("I am a block."); });
```

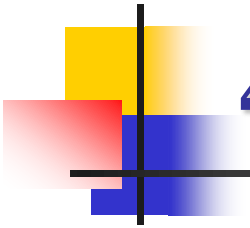
4.5.5 Intel Threading Building Blocks (TBB)

- Template library for designing parallel C++ programs
- A serial version of a simple for loop

```
for (int i = 0; i < n; i++) {
   apply(v[i]);
}
```

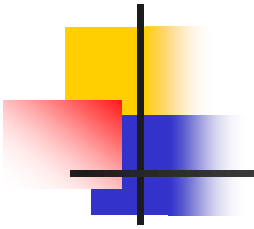
- The same for loop written using TBB with `parallel_for` statement:

```
parallel_for (size_t(0), n, [=](size_t i) {apply(v[i]);});
```



4.6 Threading Issues

- 4.6.1 fork() and exec() System Calls
- 4.6.2 Signal Handling
- 4.6.3 Thread Cancellation
- 4.6.4 Thread-Local Storage
- 4.6.5 Scheduler Activations



4.6.1 fork() & exec() System Calls

- **fork()**
  - What if one thread in a program calls fork():
    - Some UNIX systems have chosen to have two versions of fork():
      - The new process duplicates all threads
      - The new process is single-threaded (duplicates only the thread that invoked the fork()
- **exec()**
  - What if a thread invokes the exec() system call?
    - The program specified in the parameter to exec() will replace the entire process – including all threads.

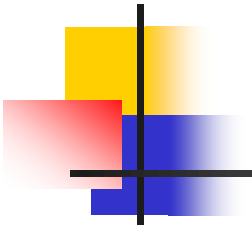
4.6.2 Signal Handling

- ***signal***
  - Used in UNIX systems to notify a process that a particular event has occurred.
- **All signals follow the same pattern:**
  - A signal is generated by the occurrence of a particular event.
  - A generated signal is delivered to a process.
  - Once delivered, the signal must be handled.

Signal Handling (Cont.)

exception

- ***Synchronous signal***
  - A running program performs some actions, e.g., illegal memory access or division by zero, a signal is generated.
  - Synchronous signals are delivered to the same process that performed the operation causing the signal
- ***Asynchronous signal***
  - A signal generated by an event external to a running process, that process receives the signal asynchronously.
  - e.g., terminate a process with CTRL-C or timer expire
  - Typically, an asynchronous signal is sent to another process.



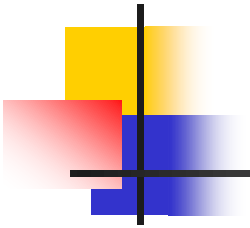
Signal Handling (Cont.)

- **Every signal may be handled by one of two possible handlers:**
  - A default signal handler
    - that kernel runs when handling signal
  - A user-defined signal handler
    - can override default

```c
#include <stdio.h>
#include <signal.h>

void sighup();
void sigint();
void sigquit();

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

    if ((pid = fork()) == 0) {
        printf("this is child process for receiving signal\n");
        signal(SIGHUP, sighup);
        signal(SIGINT, sigint);
        signal(SIGQUIT, sigquit);
        for(;;);
    } else {
        printf("this is parent process for sending signal\n");
        printf("\nPARENT: sending SIGHUP\n\n");
        kill(pid,SIGHUP);
        printf("\nPARENT: sending SIGINT\n\n");
        kill(pid,SIGINT);
        printf("\nPARENT: sending SIGQUIT\n\n");
        kill(pid,SIGQUIT);
        kill(pid,SIGHUP);
        kill(pid,SIGINT);
    }
}
void sighup() {
        printf("CHILD: I have received a SIGHUP\n");
}
void sigint() {
        printf("CHILD: I have received a SIGINT\n");
}
void sigquit() {
    printf("My DADDY has Killed me!!!\n");
}
```

user-defined signal handlers

sending signals to process



Signal Handling (Cont.)

- **How to deal with signals in a multithreaded environment?**
  - Deliver the signal to the thread to which the signal applies.
    - e.g., synchronous signals
  - Deliver the signal to every thread in the process.
    - e.g., CRTL-C
  - Deliver the signal to certain threads in the process.
    - e.g., Pthreads provides **pthread_kill(threadid, signal)**
  - Assign a specific thread to receive all signals for the process.
    - e.g., Solaris 2

4.6.3 Thread Cancellation

- **The task of terminating a thread before it has completed.**
- **Thread to be canceled is target thread**
- **Asynchronous cancellation**
  - One thread immediately terminates the target thread
- **Deferred cancellation**
  - The target thread periodically checks whether it should terminate
  - Allows a thread to check if it should be canceled at a point at which it can be canceled safely.
  - Example: Pthreads refers to such points as cancellation points.

Thread Cancellation

- **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);
```

Thread Cancellation (Cont.)

- **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, 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**

Thread Cancellation in Java

- Deferred cancellation uses the `interrupt()` method, which sets the interrupted status of a thread.

```
Thread worker;

 . . .

/* set the interruption status of the thread */
worker.interrupt()
```

- A thread can then check to see if it has been interrupted:

```
while (!Thread.currentThread().isInterrupted()) {
    . . .
}
```

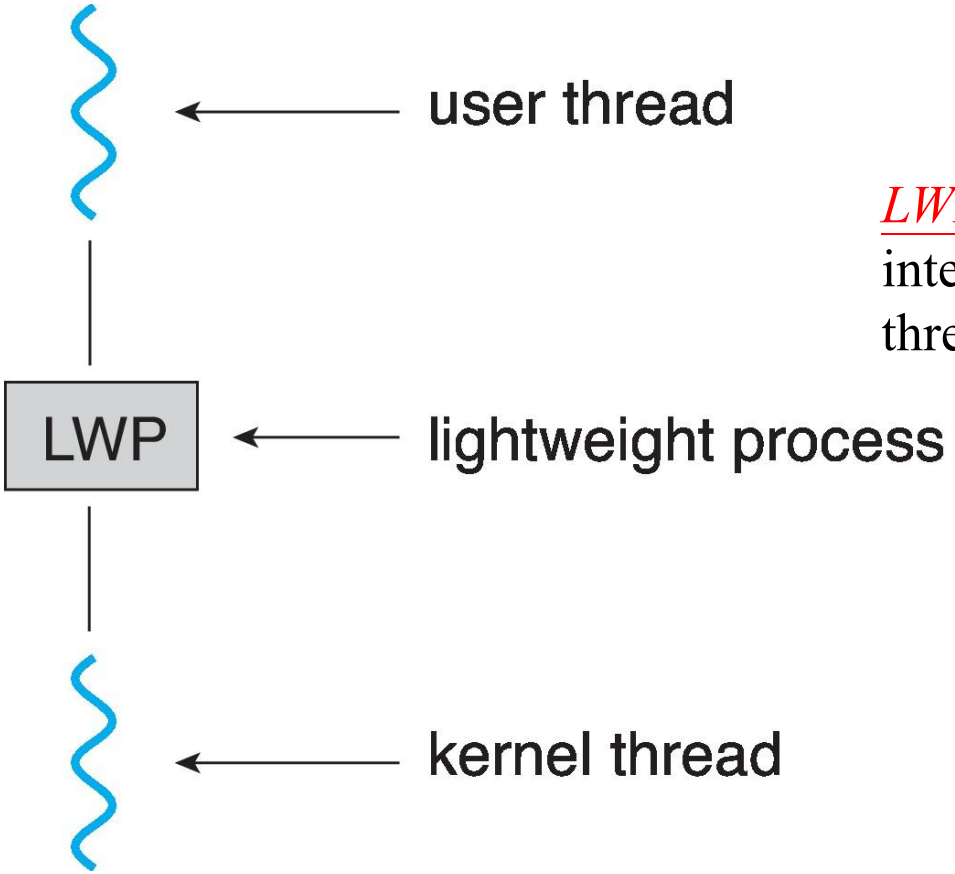
4.6.4 Thread-Local Storage

- **Each thread might need its own copy of certain data in some circumstances – thread-local storage (TLS).**
  - Visible across function invocations
- **Most thread libraries – including Windows and Pthreads – provide some form of support for thread-local storage.**
- **Java provides support as well.**

4.6.5 Scheduler Activations

- **Concerns communication between the kernel and the thread library.**
- **Both many-to-many and two-level models require communication to maintain the appropriate number of kernel threads allocated to the application**
- **Typically use an intermediate data structure between user and kernel threads – lightweight process (LWP)**
  - Appears to be a virtual processor on which the application can schedule a user thread to run
  - Each LWP is attached to a kernel thread

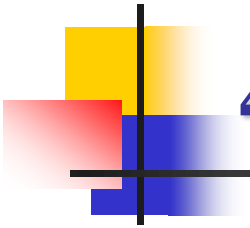
Lightweight process (LWP)



LWP (lightweight processes) - intermediate level between user-level threads and kernel-level threads.

Scheduler Activations (Cont.)

- **Scheduler activations provide upcalls - a communication mechanism from the kernel to the thread library**
  - Upcalls are handled by the thread library with an *upcall handler*
- **This communication allows an application to maintain the correct number kernel threads**



4.7 Operating-System Examples

- **Explore how threads are implemented in Windows and Linux systems.**
  - 4.7.1 Windows Threads
  - 4.7.2 Linux Threads

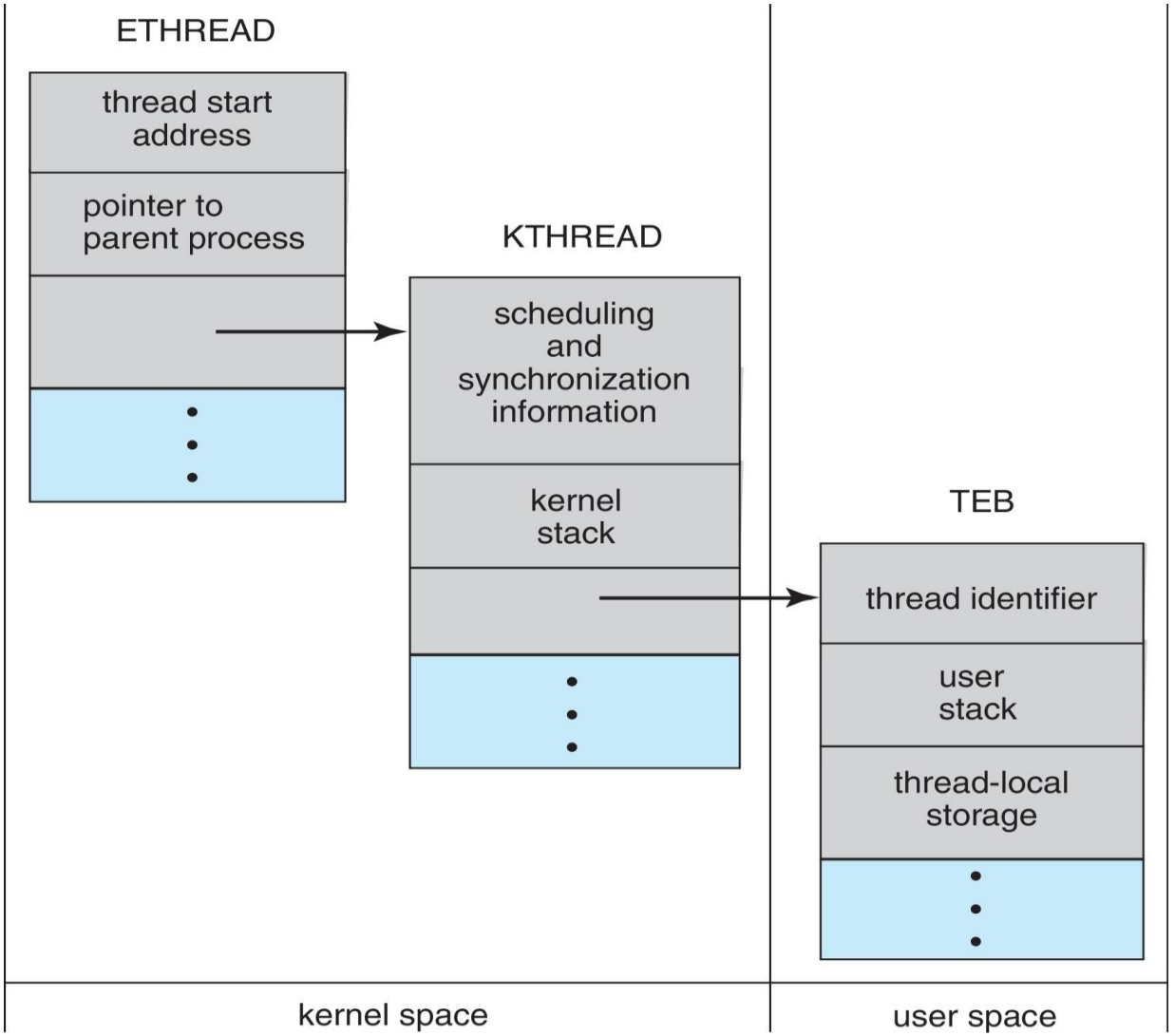
4.7.1 Windows Threads

- Windows implements the Windows API.
- A Windows application runs as a separate process, and each process may contain one or more threads.
- Implements the one-to-one mapping, where each user-level thread maps to an associated kernel thread.

Windows Threads (Cont.)

- **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 threads**
- **The primary data structures of a thread include:**
  - ETHREAD (executive thread block)
  - KTHREAD (kernel thread block)
  - TEB (thread environment block)

Data structures of a Windows thread



4.7.2 Linux Threads

- **Linux does not distinguish between processes and threads.**
  - Linux generally uses the term ***tasks*** rather than *process* or *threads* when referring to a flow of control within a program.
- **Thread creation is done through clone() system call.**
- **clone() allows a child task to share the address space of the parent task (process).**
  - the passed flags determine how much sharing between parent & child

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.

Homework

- **10th edition**
  - Ex. 4.4, 4.5, 4.6, 4.9, 4.11, 4.17, 4.19
  - Ex. 4.19 手寫 (40%) 或程式實作 (50%)
    - if (手寫)
      - 最高得 40分
    - else
      - 最高得 50分
    - 請印出執行結果畫面 (使用自己的帳號和虛擬機).
    - 請交原始程式

EX 4.19

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

int value = 0;
void *runner(void *param); /* the thread */

int main(int argc, char *argv[])
{
pid_t pid;
pthread_t tid;
pthread_attr_t attr;

   pid = fork();

   if (pid == 0) { /* child process */
      pthread_attr_init(&attr);
      pthread_create(&tid,&attr,runner,NULL);
      pthread_join(tid,NULL);
      printf("CHILD: value = %d",value); /* LINE C */
   }
   else if (pid > 0) { /* parent process */
      wait(NULL);
      printf("PARENT: value = %d",value); /* LINE P */
   }
}

void *runner(void *param) {
   value = 5;
   pthread_exit(0);
}
```