# CHAPTER 4 - MULTITHREADED PROGRAMMING

# OBJECTIVES

- Introduce notion of thread → a fundamental unit of CPU utilization
  - forms the basis of multithreaded computer systems
- Discuss the APIs for the Pthreads, Windows, and Java thread libraries
- Explore several strategies that provide implicit threading
- Examine issues related to multithreaded programming
- OS support for threads in Windows and Linux

# OVERVIEW

# MOTIVATION

- Most modern applications are multithreaded
- Threads run within application
- Multiple tasks with the application can be implemented by separate threads
  - Update display
  - Fetch data
  - Spell checking
  - Answer a network request

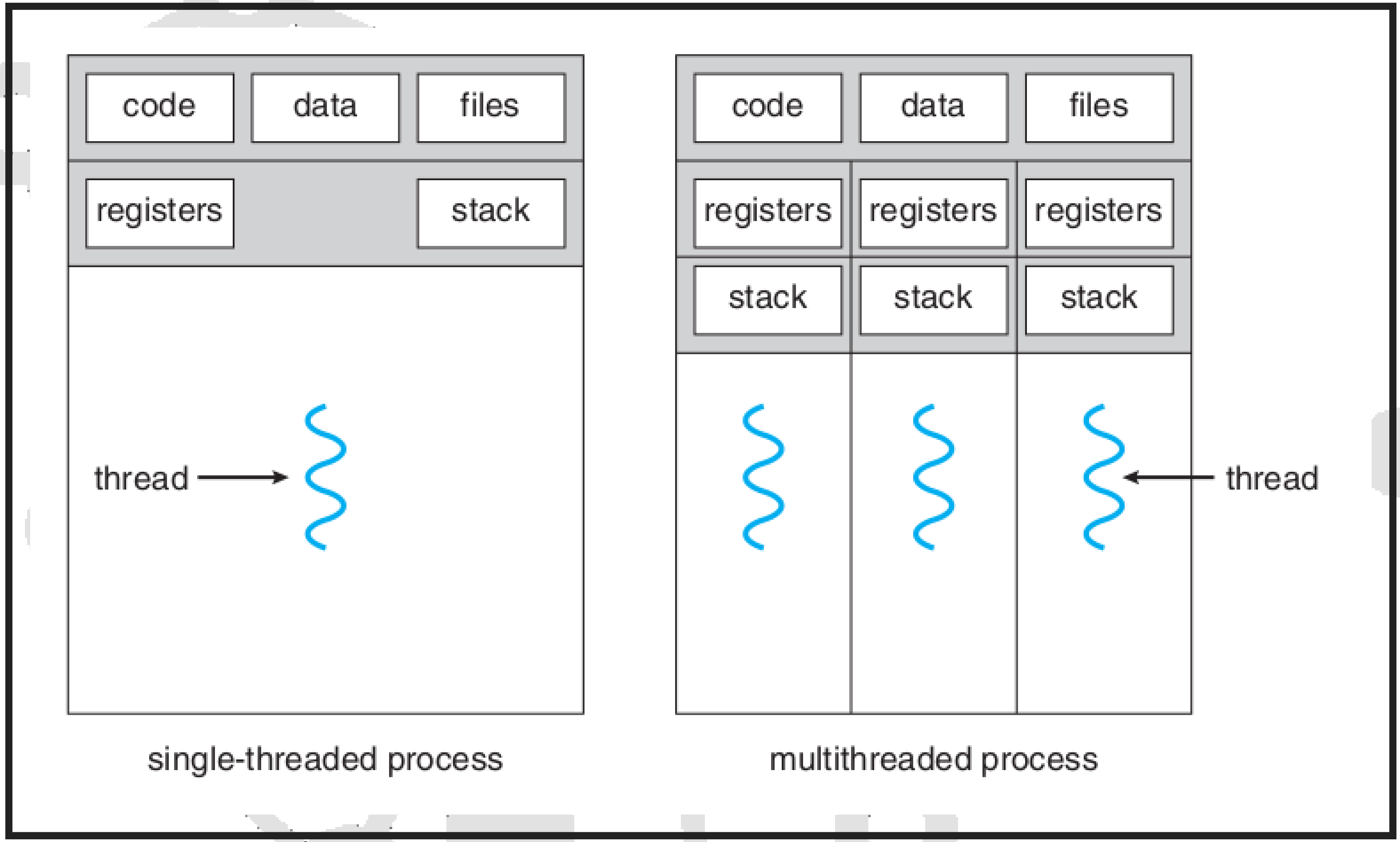
# MOTIVATION

- Process creation is heavy-weight while thread creation is light-weight
- Can simplify code, increase efficiency
- Kernels are generally multithreaded

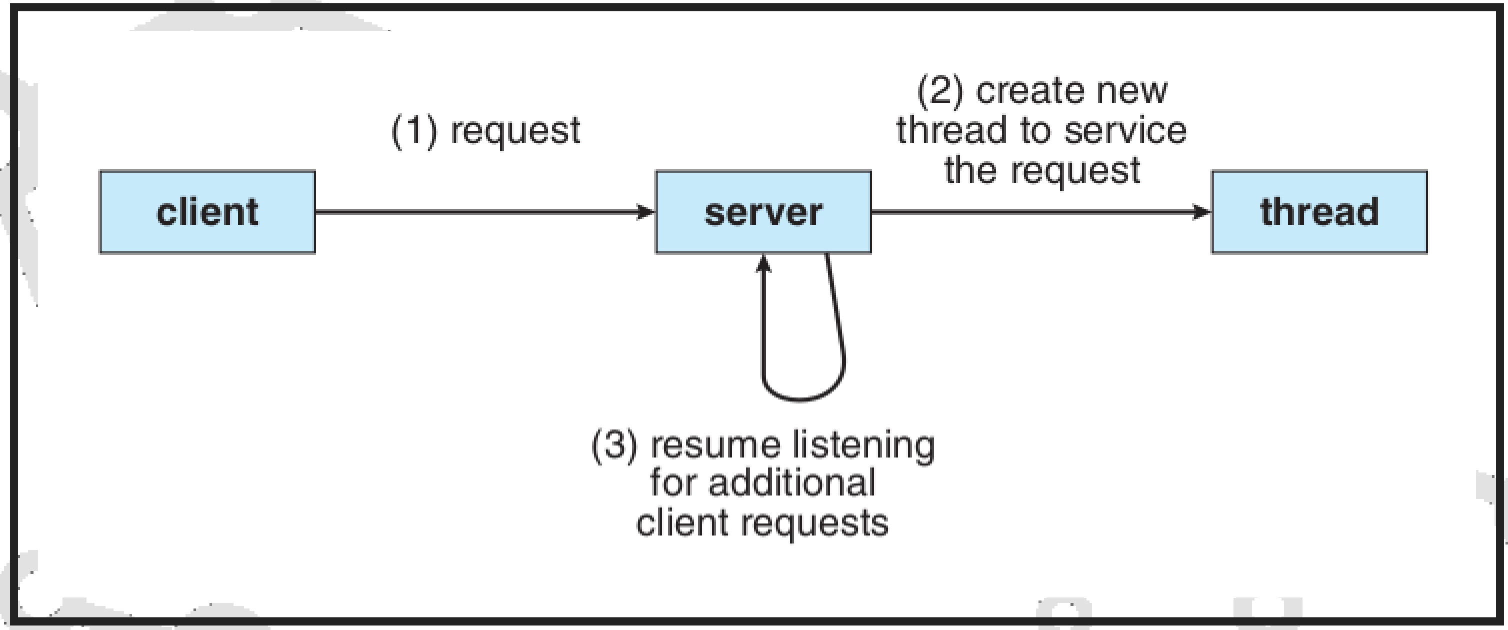
# THREAD

- Basic unit of computation
  - Thread ID
  - Program counter
  - Register set
  - Stack
  - Shares
- Shares code, data, OS resources with other threads

# SINGLE AND MULTITHREADED PROCESSES



# MULTITHREADED SERVER ARCHITECTURE



# BENEFITS

- **Responsiveness** – may allow continued execution if part of process is blocked, especially important for user interfaces
- **Resource Sharing** – threads share resources of process, easier than shared memory or message passing
- **Economy** – cheaper than process creation, thread switching lower overhead than context switching
- **Scalability** – process can take advantage of multiprocessor architectures

# MULTICORE PROGRAMMING

# MULTICORE PROGRAMMING

Multicore or multiprocessor systems putting pressure on programmers, challenges include:

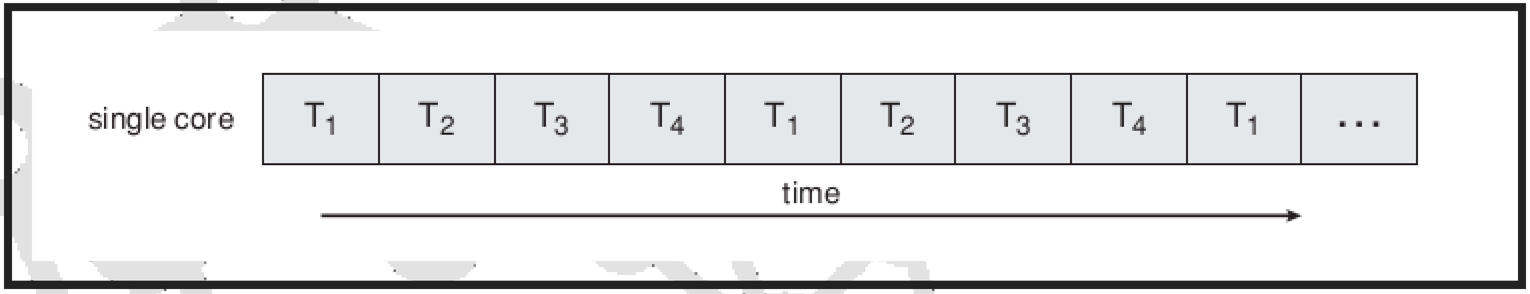
- Dividing activities
- Balance
- Data splitting
- Data dependency
- Testing and debugging

# PARALLELISM VS CONCURRENCY

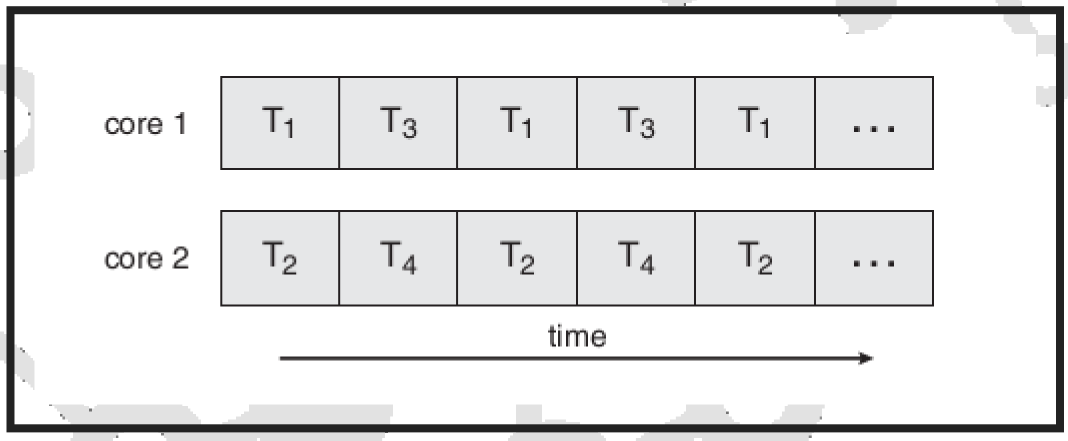
- Parallelism implies a system can perform more than one task simultaneously
- Concurrency supports more than one task making progress
  - Single processor / core, scheduler providing concurrency

# PARALLELISM VS CONCURRENCY

Concurrent execution on single-core system:




Parallelism on a multi-core system:



# TYPES OF PARALLELISM

- **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
- **Task parallelism** – distributing threads across cores, each thread performing unique operation As # of threads grows, so does architectural support for threading

CPUs have cores as well as hardware threads

Consider Oracle SPARC T4 with 8 cores, and 8 hardware threads per core

# AMDAHL'S LAW

Identifies performance gains from adding additional cores to an application that has both serial and parallel components

- S is serial portion
- N processing cores

$$\boxed{speedup \leq \frac{1}{S + \frac{(1-S)}{N}}}$$

# AMDAHL'S LAW

If application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times

- As N approaches infinity, speedup approaches 1 / S

Serial portion of an application has disproportionate effect on performance gained by adding additional cores

- But does the law take into account contemporary multicore systems?

# MULTITHREADING MODELS

# USER THREADS

User threads - management done by user-level threads library

Three primary thread libraries:

- POSIX Pthreads
- Win32 threads
- Java threads

# KERNEL THREADS

Kernel threads - Supported by the Kernel

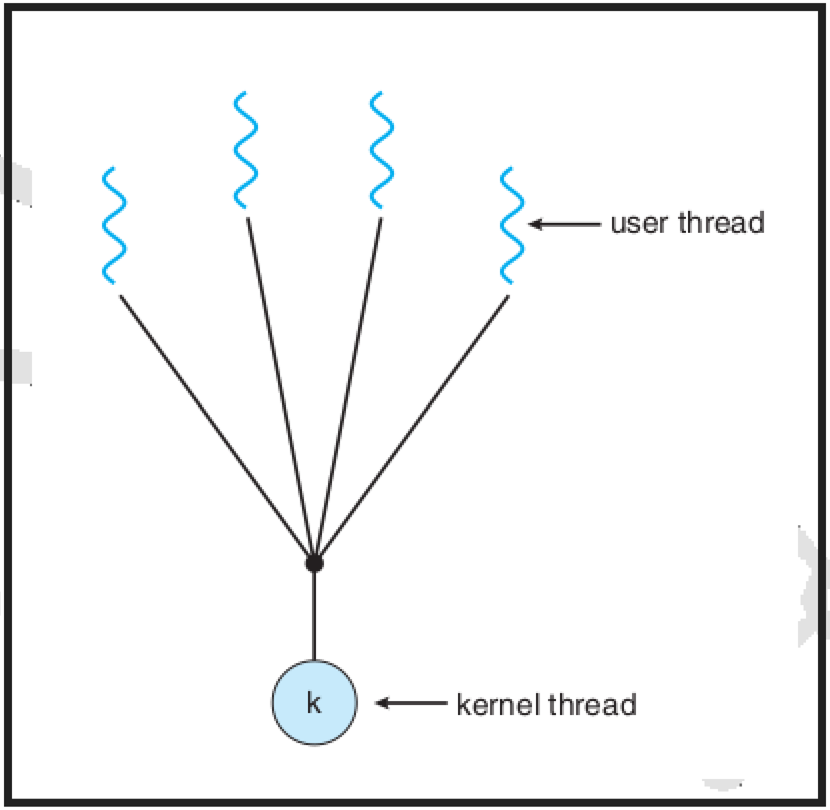
Examples – virtually all general purpose operating systems, including:

- Windows
- Solaris
- Linux
- Tru64 UNIX
- Mac OS X

# MULTITHREADING MODELS

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

# MANY-TO-ONE

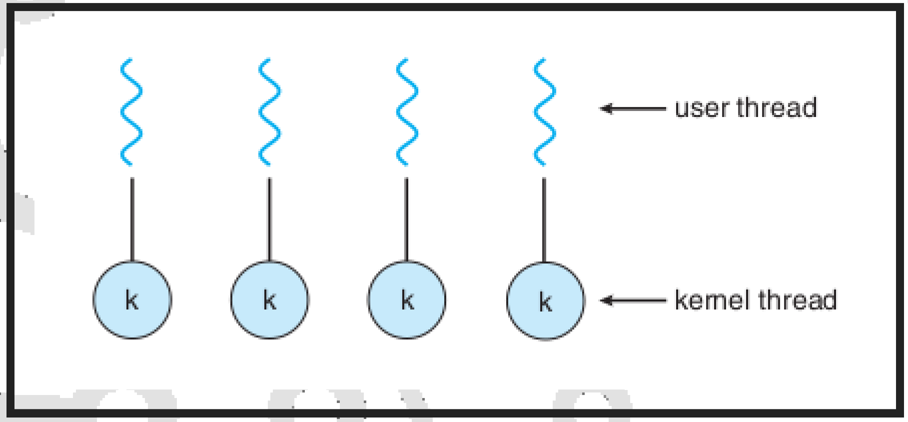


# MANY-TO-ONE

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

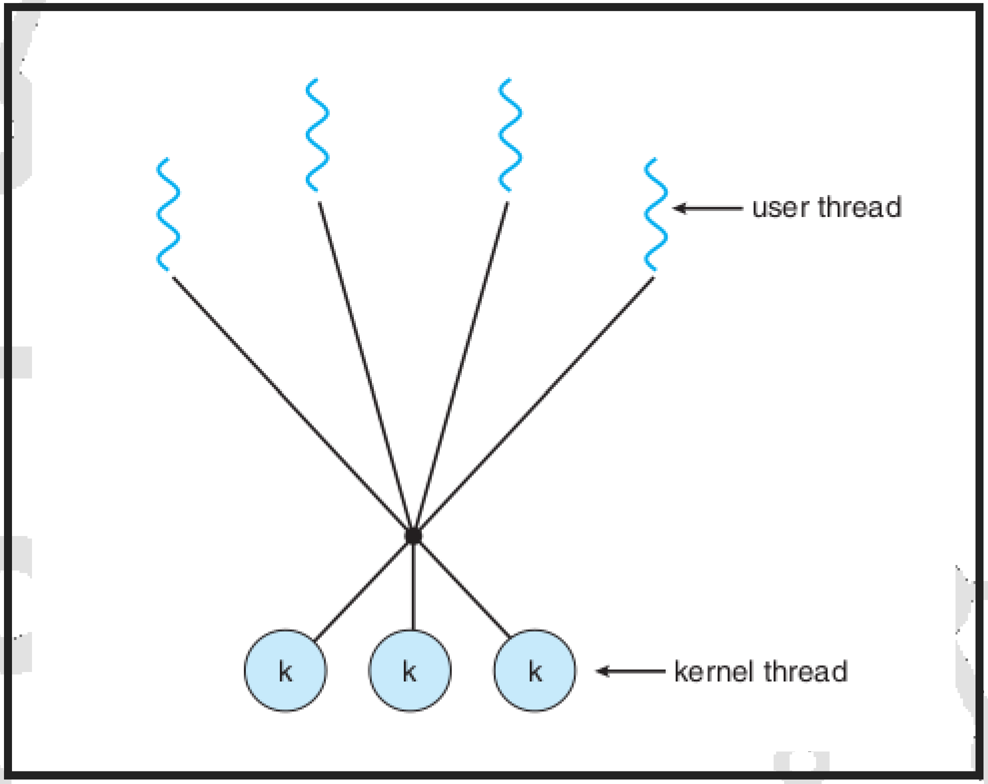
# ONE-TO-ONE



# 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 NT/XP/2000
  - Linux
  - Solaris 9 and later

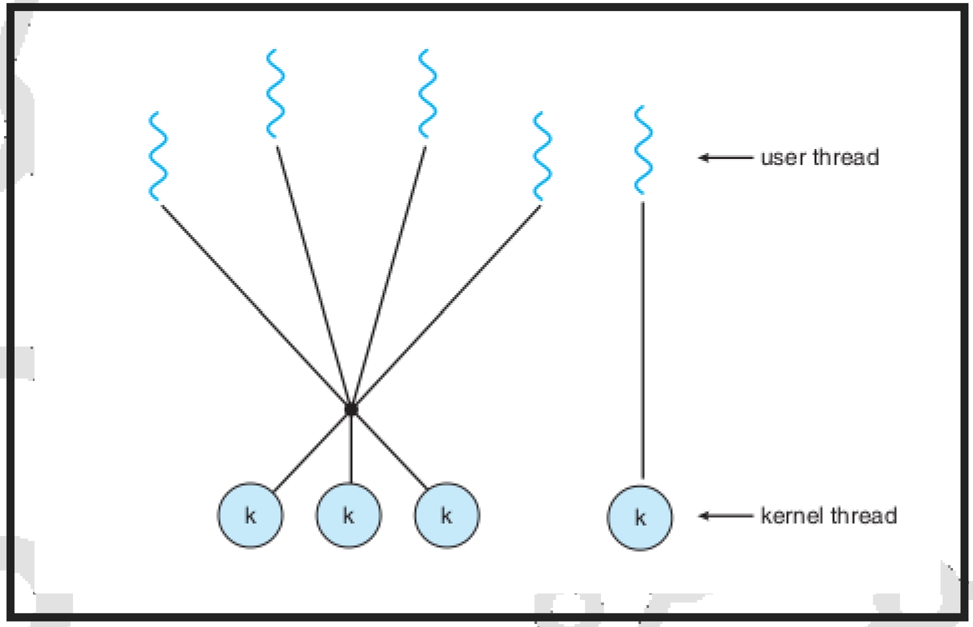
# MANY-TO-MANY



# 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 NT/2000 with the ThreadFiber package

# TWO-LEVEL MODEL



# TWO-LEVEL MODEL

- Similar to M:M, except that it allows a user thread to be bound to kernel thread
- Examples
  - IRIX
  - HP-UX
  - Tru64 UNIX
  - Solaris 8 and earlier

# THREAD LIBRARIES

# THREAD LIBRARIES

- 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

# PTHREADS

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

# PTHREADS EXAMPLE

```c
#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]));
```

# PTHREADS CODE FOR JOINING 10 THREADS

```
#define NUM THREADS 10

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

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

# WIN API MULTITHREADED

```c
#include <windows.h>
#include <stdio.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;
}
int main(int argc, char *argv[]) {
    DWORD ThreadId;
    HANDLE ThreadHandle;
    int Param;
```

# JAVA THREADS

- Java threads are managed by the JVM
- Typically implemented using the threads model provided by underlying OS
- Java threads may be created by:
  - Extending Thread class
  - Implementing the Runnable interface

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

# JAVA MULTITHREADED PROGRAM

```
class Sum {
    private int sum;
    public int getSum() {
            return sum;
    }
    public void setSum(int sum) {
        this.sum = sum;
    }
}
```

# JAVA MULTITHREADED PROGRAM

```
class Summation implements Runnable  {
    private int upper;
    private Sum sumValue;
    public Summation(int upper, Sum sumValue) {
        this.upper = upper;
        this.sumValue = sumValue;
    }
    public void run() {
        int sum = 0;
        for (int i = 0; i <= upper; i++)
            sum += i;
        sumValue.setSum(sum);
    }
}
```

# JAVA MULTITHREADED PROGRAM

```
public class Driver {
  public static void main(String[] args) {
    if (args.length > 0) {
      if (Integer.parseInt(args[0]) < 0) {
        System.err.println(args[0] + " must be >= 0.");
      } else {
        Sum sumObject = new Sum();
        int upper = Integer.parseInt(args[0]);
        Thread thrd = new Thread(new Summation(upper, sumObject));
        thrd.start();
        try {
          thrd.join();
          System.out.println("The sum of "+upper+" is "+sumObject.get
        } catch (InterruptedException ie) { }
      }
    } else {
```

# IMPLICIT THREADING

# 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

# IMPLICIT THREADING

- Three methods explored
  - Thread Pools
  - OpenMP
  - Grand Central Dispatch
- Other methods include Microsoft Threading Building Blocks (TBB), `java.util.concurrent` package

# THREAD POOLS

Create a number of threads in a pool where they await work

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
- 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

# THREAD POOLS

Windows API supports thread pools:

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

# GPARS

```groovy
import static groovyx.gpars.GParsPool

// Calculate the n'th fibonacci number
def fibonnacci( n ) {
	if( n < 2) {
		return 1
	}
	fibonnacci(n-1) + fibonnacci(n-2)
}

GParsPool.withPool {
	(1..50).eachParallel { int i ->
		def tId = Thread.currentThread().getId()
		println "${i} fib number: ${fibonnacci(i)} ${tId}"
	}
}
```

# OPENMP

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

# OPENMP EXAMPLE

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

// Compile using:
// gcc -fopenmp  omp.c
int main(int argc, char *argv[]) {

    #pragma omp parallel
    {
        printf("I am a parallel region.\n");
    }
    return 0;
}
```

# OPENMP EXAMPLE

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

// Compile using:
// gcc -fopenmp  omp2.c
int main(int argc, char *argv[]) {

    int i;

    #pragma omp parallel for
    for( i = 0; i < 20; i++ ) {
        printf("I am a parallel for loop: %i.\n", i);
    }
    return 0;
}
```

# GRAND CENTRAL DISPATCH

- Apple technology for Mac OS X and iOS operating systems
- Extensions to C, C++ languages, API, and run-time library
- Allows identification of 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

- 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

# THREADING ISSUES

# THREADING ISSUES

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

# SEMANTICS

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

- Does `fork()` duplicate only the calling thread or all threads?
  - Some UNIXes have two versions of 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.
- A **signal handler** is used to process signals

1. Signal is generated by particular event
2. Signal is delivered to a process
3. Signal is handled by one of two signal handlers:
    1. default
    2. user-defined

# SIGNAL HANDLING

Every signal has default handler that kernel runs when handling signal

- User-defined signal handler can override default
- For single-threaded, signal delivered to process

# SIGNAL HANDLING

Where should a signal be delivered for multi-threaded?

- 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

# THREAD CANCELLATION

- Terminating a thread before it has finished
- Thread to be canceled is target thread
- Two general approaches:
  - Asynchronous cancellation terminates the target thread immediately
  - Deferred cancellation allows the target thread to periodically check if it should be cancelled

# 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);
```

# THREAD CANCELLATION

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

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

# THREAD CANCELLATION

- 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-LOCAL STORAGE

- **Thread-local storage** (**TLS**) allows each thread to have its own copy of data
- Useful when you do not have control over the thread creation process (i.e., when using a thread pool)

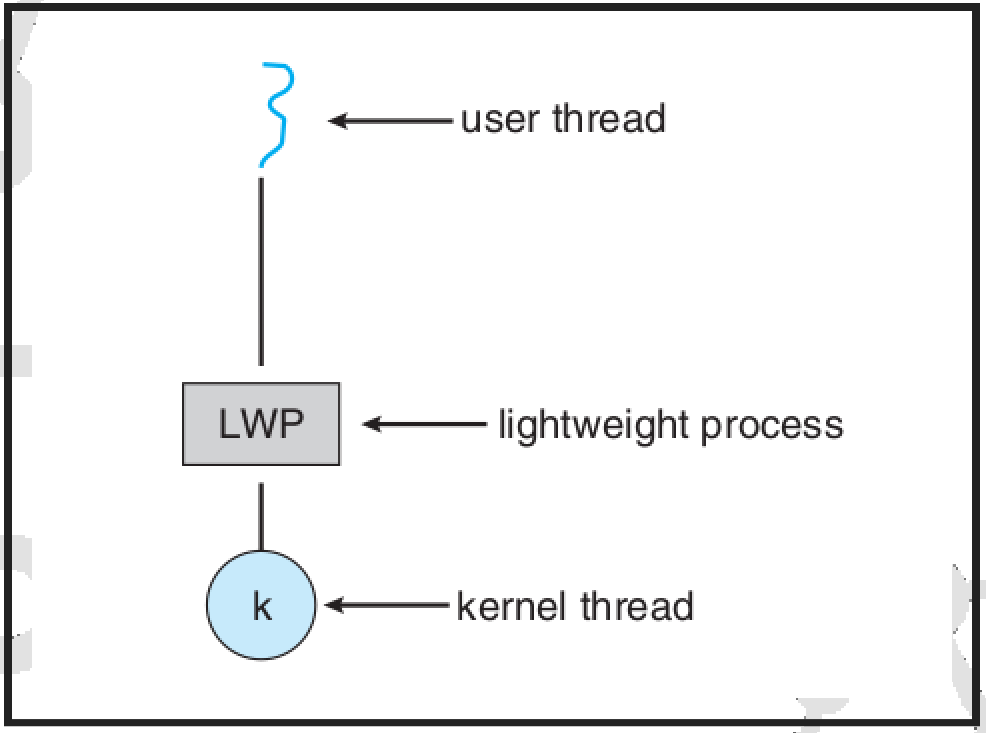
# THREAD-LOCAL STORAGE

- Different from local variables
  - Local variables visible only during single function invocation
  - TLS visible across function invocations
- Similar to static data
  - TLS is unique to each thread

# SCHEDULER ACTIVATIONS

- Both M:M 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 process can schedule user thread to run
  - Each LWP attached to kernel thread
  - How many LWPs to create?

# SCHEDULER ACTIVATIONS



# SCHEDULER ACTIVATIONS

- Scheduler activations provide upcalls - a communication mechanism from the kernel to the upcall handler in the thread library
- This communication allows an application to maintain the correct number kernel threads

# OPERATING SYSTEM EXAMPLES

# OPERATING SYSTEM EXAMPLES

- Windows XP Threads
- Linux Thread

# WINDOWS THREADS

Windows implements the Windows API – primary API for Win 98, Win NT, Win 2000, Win XP, and Win 7

- Implements the one-to-one mapping, kernel-level

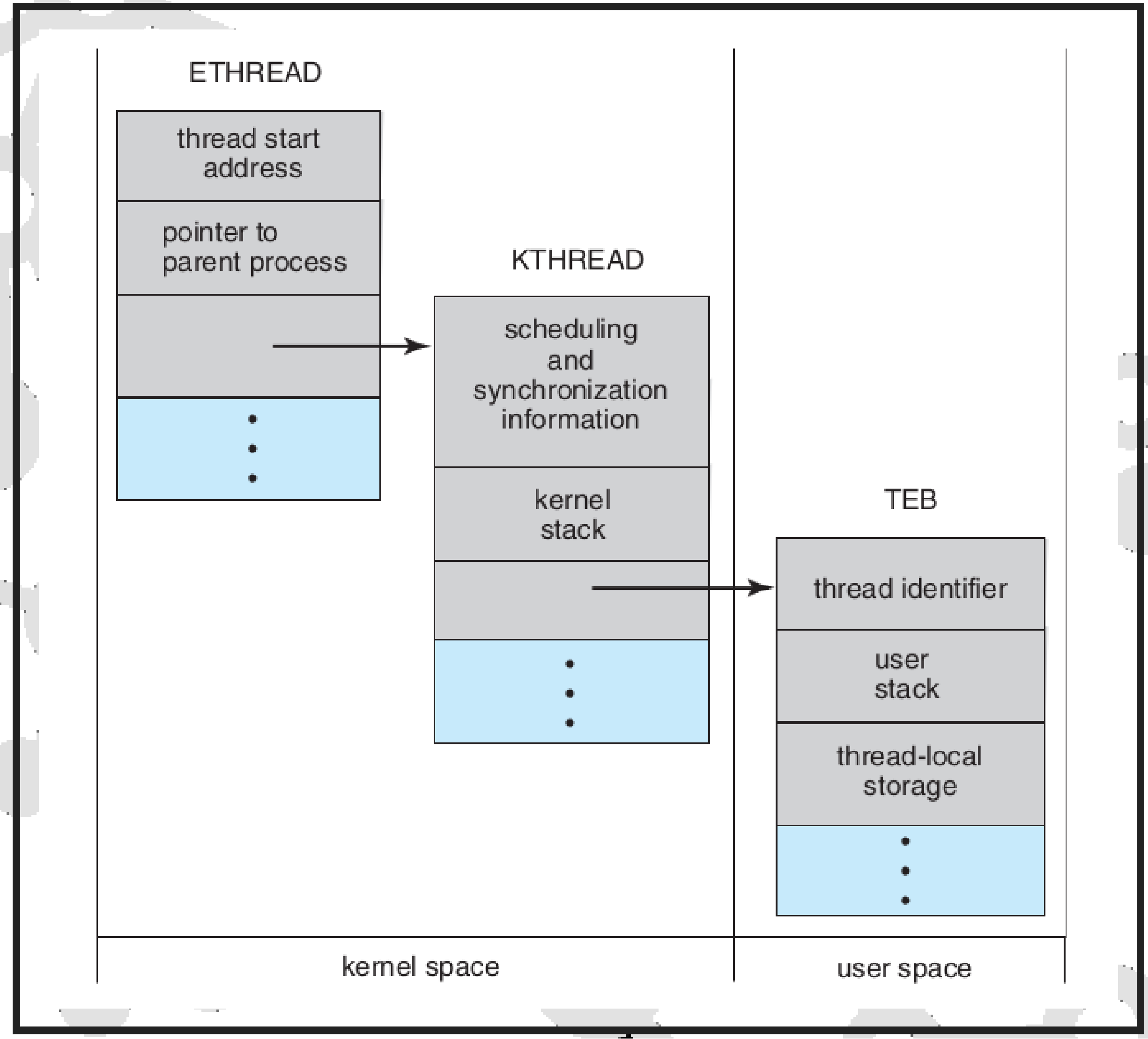
# WINDOWS THREADS

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

# WINDOWS THREADS

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

# WIN XP THREADS DATA STRUCTURES



# LINUX THREADS

Linux refers to them as tasks rather than threads

- Thread creation is done through `clone()` system call

# LINUX THREADS

- `clone()` allows a child task to share the address space of the parent task (process)
  - Flags control behavior

| 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. |

- `struct task_struct` points to process data structures (shared or unique)

# QUESTIONS

# BONUS

- Exam question number 2: **Process Concept and Multithreaded Programming**