Chapter 2: Process Management

2.2. Threads & Concurrency

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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 operating systems represent threads
- Design multithreaded applications using the Pthreads, Java, and Windows threading APIs

Outline

- Overview
- Multicore Programming
- Multithreading Models
- Thread Libraries
- Implicit Threading
- Threading Issues
- Operating System Examples

Introduction to computer system

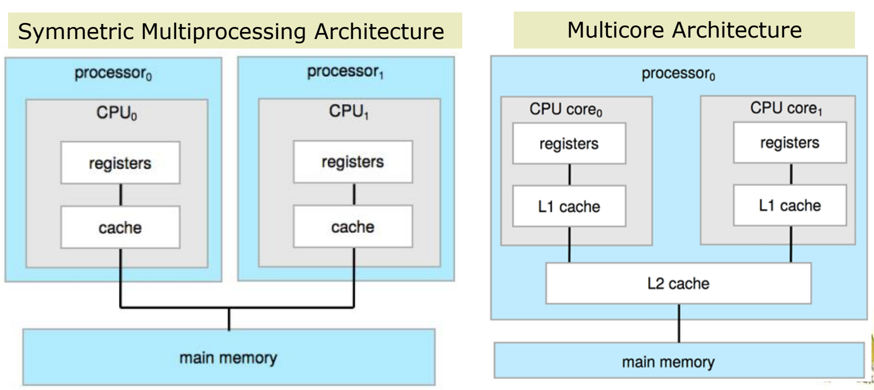
- Processor — A physical chip that contains one or more CPUs.
- CPU —The hardware that executes instructions.
- Core —The basic computation unit of the CPU.
- Two types of core processor:
  - Single-Core Processor: makes the processor inefficient
    - To execute the tasks faster, you need to increase the clock time => increases power consumption and heat dissipation => **inefficient**
  - Multi-Core Processor: multiple computing cores on the same CPU.
    - increase the processing power while it also keeps clock speed at an efficient level. => process consumes less energy
- Multiprocessor — Including multiple processors

Processing in computer

- Multiprogramming: (Multi Job or Multiprocess) – the important in OS
  - organizes jobs (code and data) so CPU always has one to execute
  - several processes in memory simultaneously
  - OS picks and begins to execute one of these processes
- In old OSs: a process was executed with a **single thread** of control.
  - Thread: a unit of execution on concurrent programming
- Virtually all modern OSs provide features enabling a process to contain **multiple threads** of control.
  - Multithreading allows a CPU to execute many tasks of one process at the same time
- Identifying opportunities for parallelism through the use of threads is becoming increasingly important for modern **multicore systems** that provide multiple CPUs (Most applications are multithreaded)
  - An application typically is implemented as a separate process with several threads of control.

MultiCore Systems

- The **core** is the component that executes instructions and registers for storing data locally
- **Multicore** systems can be more efficient than multiple chips with single cores
  - because on-chip communication is faster
  - one chip with multiple cores uses significantly less power

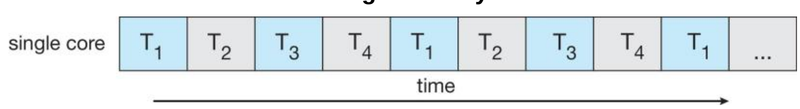


Multicore Programming

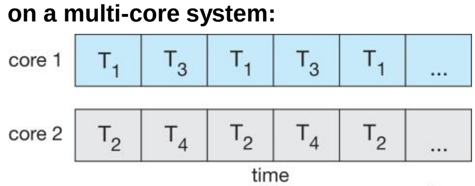
- On a system with a single core
  - **Concurrency** merely means that the execution of the threads will be interleaved over time because the processing core is capable of executing only one thread at a time.
- On a system with multiple cores
  - **concurrency** means that some threads can run in parallel, because the system can assign a separate thread to each core
- The systems as **multicore** and **multithreaded** programming provides a mechanism for more efficient use of these multiple computing cores and improved concurrency.

Concurrency vs. Parallelism

- **Distinguish:**
  - A **concurrent** system supports more than one task by allowing all the tasks to make progress.
  - In contrast, a **parallel** system can perform more than one task simultaneously.
- **Concurrent execution on single-core system:**



- **Parallelism on a multi-core system:**

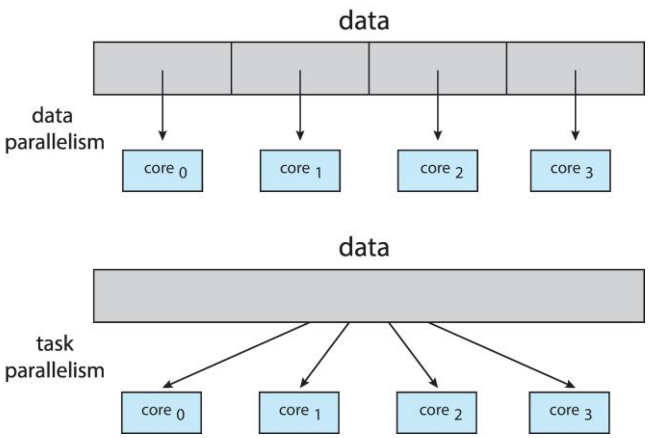


- **Thus, it is possible to have concurrency without parallelism**

Data and Task Parallelism

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**



Amdahl's Law

- Amdahl's law is often used in parallel computing to predict the theoretical speedup when using multiple processors
- Identifies performance gains from adding additional cores to an application that has both serial and parallel components
- *S* is serial portion, *N* processing cores

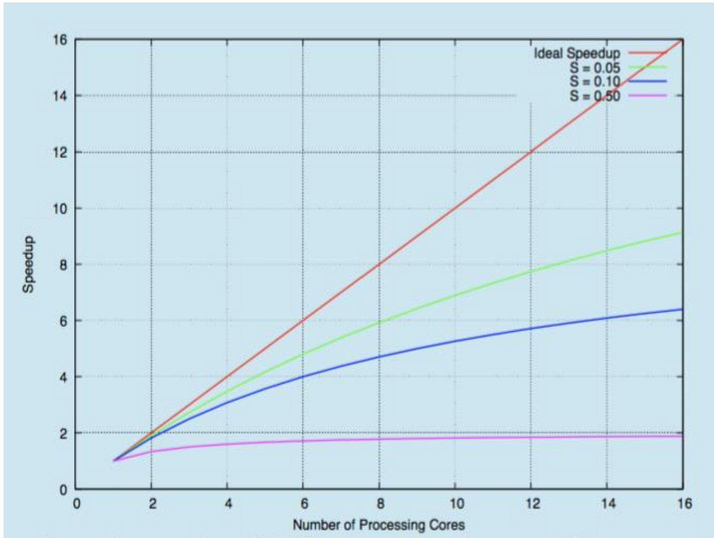
$$speedup \le \frac{1}{S + \frac{(1-S)}{N}}$$

- Ex: if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times.
  - If we add **two** additional cores (for a total of four), the speedup is **?**
- 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?

Amdahl's Law

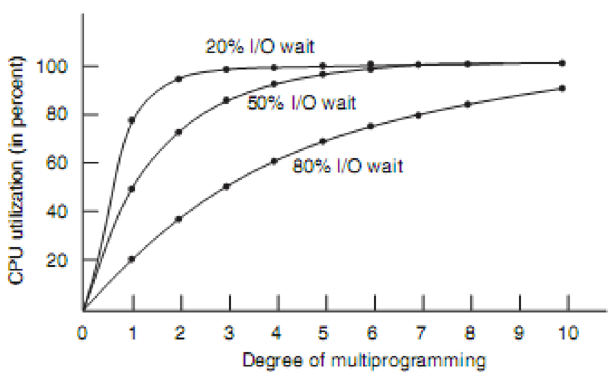


Overhead for: Scheduling, Synchronization, Communication, etc

Modeling Multiprogramming

- When multiprogramming is used, the CPU utilization can be improved.
- The CPU utilization as a function of n, which is called the degree of multiprogramming (describes the maximum number of processes that a single-processor system can accommodate efficiently).

$$\text{CPU utilization} = 1 - p^n$$



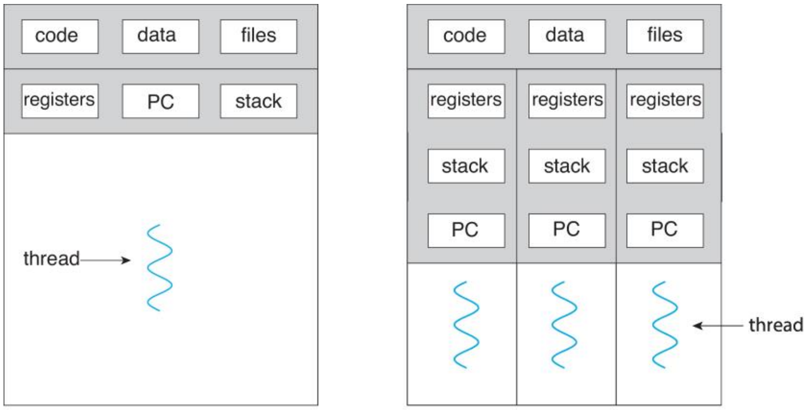
Programming Challenges

- 1. **Identifying tasks**.
  - examining applications to find areas that can be divided into separate, concurrent tasks. Ideally, tasks are independent of one another and thus can run in parallel on individual cores.
- **2. Balance**.
  - ensure that the tasks perform equal work of equal value. In some instances, a certain task may not contribute as much value to the overall process as other tasks. Using a separate execution core to run that task may not be worth the cost.
- **3. Data splitting.**
  - the data used by the tasks must be divided to run on separate cores.
- **4. Data dependency**.
  - When one task depends on data from another, programmers must ensure that the execution of the tasks is synchronized to accommodate the data
- **5. Testing and debugging**.
  - more difficult than testing and debugging single-threaded applications.
- **=> the advent of multicore systems will require an entirely new approach to designing software systems in the future**

Motivation for Multithreaded Architectures

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

Single and Multithreaded Processes

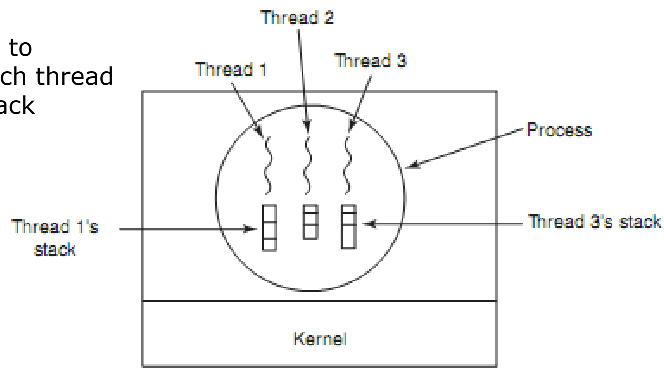


single-threaded process

multithreaded process

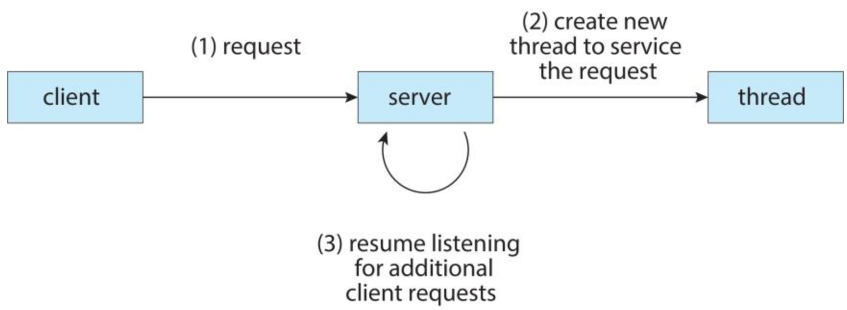
Multithread

It is important to realize that each thread has its own stack
Why?



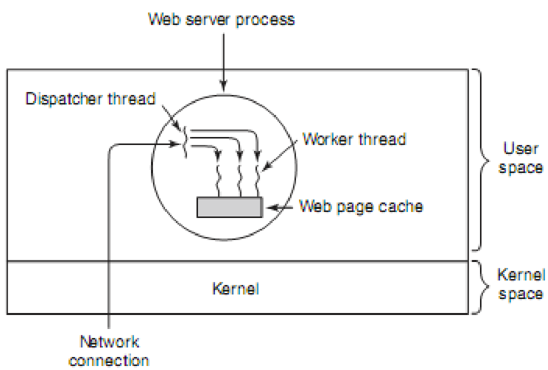
Per-process items	Per-thread items
Address space	Program counter
Global variables	Registers
Open files	Stack
Child processes	State
Pending alarms	
Signals and signal handlers	
Accounting information	

Multithreaded Server Architecture



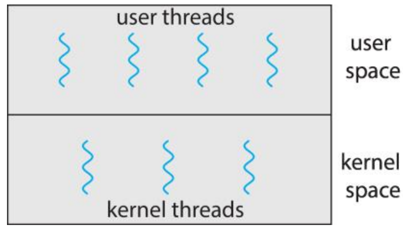
Benefits

- **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 multicore architectures
- Ex:



User Threads and Kernel Threads

- **User threads** - management done by user-level threads library
- Three primary thread libraries:
  - POSIX **Pthreads**
  - Windows threads
  - Java threads



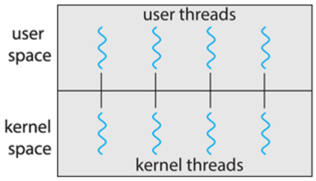
- **Kernel threads** - Supported by the Kernel
- Most OS kernels are also typically multithreaded, including:
  - Windows, Linux, Mac OS X, iOS, Android
  - Ex The command ps -ef can be used to display the kernel threads on a running Linux system

User Threads and Kernel Threads

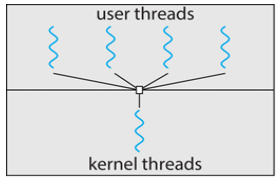
USER LEVEL THREAD	KERNEL LEVEL THREAD
User thread are implemented by user processes.	kernel threads are implemented by OS.
OS doesn't recognized user level threads.	Kernel threads are recognized by OS.
Implementation of User threads is easy.	Implementation of Kernel thread is complicated.
Context switch time is less.	**Context switch time is more.**
Context switch requires no hardware support.	Hardware support is needed.
If one user level thread perform blocking operation then entire process will be blocked.	If one kernel thread perform blocking operation then another thread can continue execution.
Example : Java thread, POSIX threads.	Example : Window Solaris.

Multithreading Models

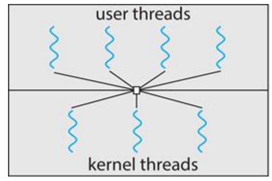
- One-to-One



- Many-to-One



- Many-to-Many



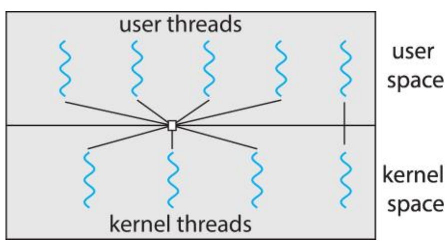
- Each user-level thread maps to kernel thread
- Creating a user-level thread creates a kernel thread
- More concurrency than many-to-one
- Number of threads per process sometimes restricted due to overhead
- Examples
  - **Windows**
  - **Linux**

- 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**

- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Windows with the ThreadFiber package
- Otherwise not very common

Multithreading Models

- Two-level Model: Similar to Many-to-Many, except that it allows a user thread to be **bound** to kernel thread



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 (Linux & Mac OS X)

Pthreads Example

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

#include <stdlib.h>

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

  /* set the default attributes of the thread */
  pthread_attr_init(&attr);
  /* create the thread */
  pthread_create(&tid, &attr, runner, argv[1]);
  /* wait for the thread to exit */
  pthread_join(tid,NULL);

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

Pthreads Example (Cont.)

```
/* 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);
}
```

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);
```


Windows Multithreaded C Program

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

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

Windows Multithreaded C Program (Cont.)

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

   Param = atoi(argv[1]);
   /* create the thread */
   ThreadHandle = CreateThread(
      NULL, /* default security attributes */
      0, /* default stack size */
      Summation, /* thread function */
      &Param, /* parameter to thread function */
      0, /* default creation flags */
      &ThreadId); /* returns the thread identifier */

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

   /* close the thread handle */
   CloseHandle(ThreadHandle);

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


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();
}
```

  - Standard practice is to implement Runnable interface

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) { }
  }
}
```

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

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
- Windows API supports thread pools:

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

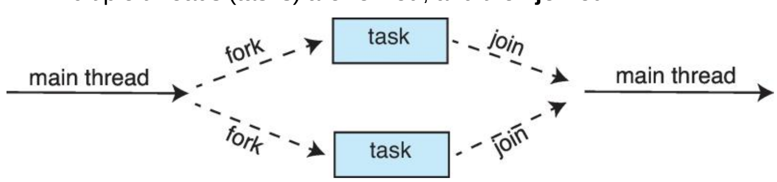
Java Thread Pools

- Three factory methods for creating thread pools in Executors class:
  - `static ExecutorService newSingleThreadExecutor()`
  - `static ExecutorService newFixedThreadPool(int size)`
  - `static ExecutorService newCachedThreadPool()`
- Ex:

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

public class ThreadPoolExample
{
public static void main(String[] args) {
   int numTasks = Integer.parseInt(args[0].trim());

   /* Create the thread pool */
   ExecutorService pool = Executors.newCachedThreadPool();

   /* Run each task using a thread in the pool */
   for (int i = 0; i < numTasks; i++)
      pool.execute(new Task());

   /* Shut down the pool once all threads have completed */
   pool.shutdown();
}
```


Fork-Join Parallelism

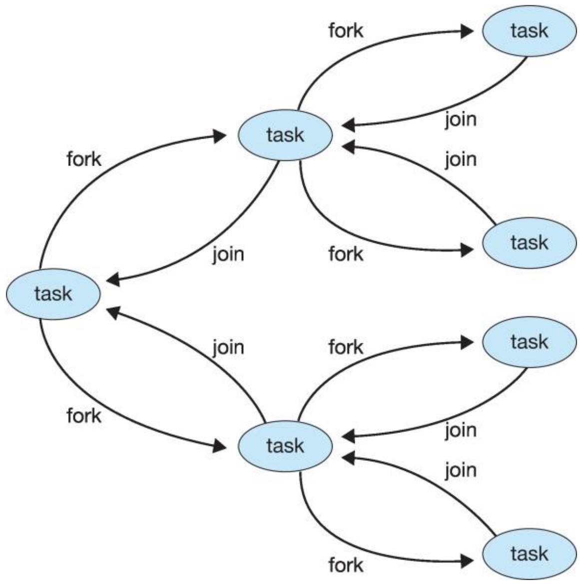
- Multiple threads (tasks) are **forked**, and then **joined**.



- 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



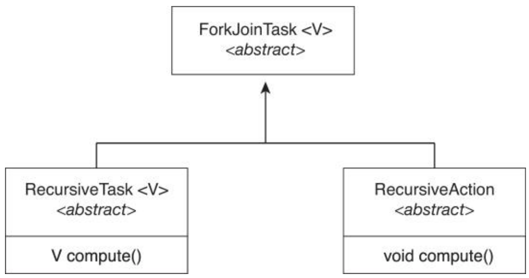
Fork-Join Parallelism in Java

```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);
```

```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



OpenMP

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

`#pragma omp parallel`

Create as many threads as there are cores

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

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

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

   /* sequential code */

   return 0;
}
```

Run the Loop in Parallel

- Run the for loop in parallel

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


Grand Central Dispatch

- Apple technology for macOS and iOS operating systems
- Extensions to C, C++ and Objective-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
    - Four system wide queues divided by quality of service:
      - `QOS_CLASS_USER_INTERACTIVE`
      - `QOS_CLASS_USER_INITIATED`
      - `QOS_CLASS_USER_UTILITY`
      - `QOS_CLASS_USER_BACKGROUND`

Grand Central Dispatch

- For the Swift language a task is defined as a closure – similar to a block, minus the caret
- Closures are submitted to the queue using the `dispatch_async()` function:

```
let queue = dispatch_get_global_queue
   (QOS_CLASS_USER_INITIATED, 0)

dispatch_async(queue,{ print("I am a closure.") })
```

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]);});
```


Threading Issues

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

Semantics of fork() and exec()

- 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
- 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 (Cont.)

- 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
- 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:

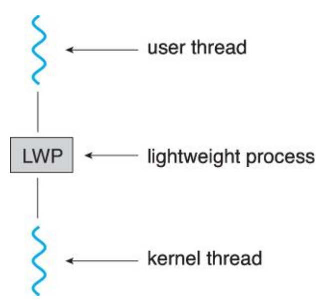
```
while (!Thread.currentThread().isInterrupted()) {
   . . .
}
```

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)
- 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 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



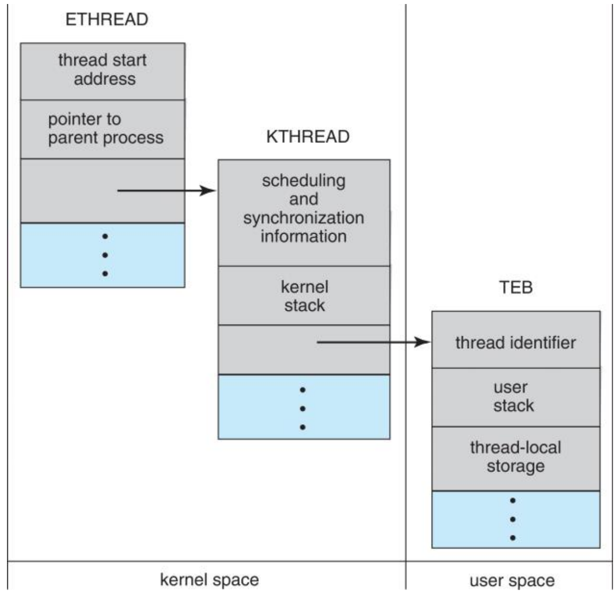
Operating System Examples

- Windows Threads
- Linux Threads

Windows Threads

- Windows API – primary API for Windows applications
- Implements the one-to-one mapping, kernel-level
- Each thread contains
  - A thread id. Register set representing state of processor
  - Separate user and kernel stacks for when thread runs in user mode or kernel mode
  - Private data storage area used by run-time libraries and DLLs
- The register set, stacks, and private storage area: the **context** of the thread
- The primary data structures of a thread include:
  - ETHREAD (executive thread block) – includes pointer to process to which thread belongs and to KTHREAD, in kernel space
  - KTHREAD (kernel thread block) – scheduling and synchronization info, kernel-mode stack, pointer to TEB, in kernel space
  - TEB (thread environment block) – thread id, user-mode stack, thread-local storage, in user space

Windows Threads Data Structures



Linux Threads

- Linux refers to them as ***tasks*** rather than ***threads***
- Thread creation is done through **`clone()`** system call
- **`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)

End of Chapter 2.2