Threads & Concurrency
Threads

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

• To introduce the notion of a thread—a fundamental unit of CPU utilization that forms the basis of multithreaded computer systems
• To discuss the APIs for the Pthreads, Windows, and Java thread libraries
• To explore several strategies that provide implicit threading
• To examine issues related to multithreaded programming
• To cover operating system support for threads in Windows and Linux
Process

Address Space

PC

...
Process Control Block (PCB)

Information associated with each process (also called **task control block**)

- Process state – running, waiting, etc
- Program counter – location of instruction to next execute
- CPU registers – contents of all process-centric registers
- CPU scheduling information - priorities, scheduling queue pointers
- Memory-management information – memory allocated to the process
- Accounting information – CPU used, clock time elapsed since start, time limits
- I/O status information – I/O devices allocated to process, list of open files

<table>
<thead>
<tr>
<th>process state</th>
</tr>
</thead>
<tbody>
<tr>
<td>process number</td>
</tr>
<tr>
<td>program counter</td>
</tr>
<tr>
<td>registers</td>
</tr>
<tr>
<td>memory limits</td>
</tr>
<tr>
<td>list of open files</td>
</tr>
</tbody>
</table>
Multiple Processors
Threads

CPU A
- PC
- GPRs
- CACHE

CPU B
- PC
- GPRs
- CACHE

Address Space

Process B
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
• Process creation is heavy-weight while thread creation is light-weight
• Can simplify code, increase efficiency
• Kernels are generally multithreaded
Multithreaded Server Architecture

1. Request
2. Create new thread to service the request
3. Resume listening for additional client requests
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** or **multiprocessor** systems putting pressure on programmers, challenges include:
  – Dividing activities
  – Balance
  – Data splitting
  – Data dependency
  – Testing and debugging

• **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
Concurrent execution on single-core system:

Parallelism on a multi-core system:
Multicore Programming (Cont.)

• 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
Single and Multithreaded Processes

- **Single-threaded process**
  - Code
  - Data
  - Files
  - Registers
  - Stack
  - Thread

- **Multithreaded process**
  - Code
  - Data
  - Files
  - Registers
  - Registers
  - Registers
  - Stack
  - Stack
  - Stack
  - Thread
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

\[ \text{speedup} \leq \frac{1}{\frac{S}{N} + \frac{(1-S)}{N}} \]

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

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

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

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

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

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

    if (argc != 2) {
        fprintf(stderr, "usage: a.out <integer value>\n");
        return -1;
    }
    if (atoi(argv[1]) < 0) {
        fprintf(stderr, "%d must be >= 0\n", atoi(argv[1]));
        return -1;
    }"
/* get the default attributes */
pthread_attr_init(&attr);
/* create the thread */
pthread_create(&tid,&attr,runner,argv[1]);
/* wait for the thread to exit */
pthread_join(tid,NULL);

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

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

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

    pthread_exit(0);
}
Pthreads Code for Joining 10 Threads

```c
#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 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;

    if (argc != 2) {
        fprintf(stderr,"An integer parameter is required\n");
        return -1;
    }
    Param = atoi(argv[1]);
    if (Param < 0) {
        fprintf(stderr,"An integer >= 0 is required\n");
        return -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 */

if (ThreadHandle != NULL) {
    /* 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:

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

– Extending Thread class
– Implementing the Runnable interface
```
Java Multithreaded Program

class Sum
{
    private int sum;

    public int getSum() {
        return sum;
    }

    public void setSum(int sum) {
        this.sum = sum;
    }
}

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);
    }
}
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.getSum());
                } catch (InterruptedException ie) {
                }
            }
        } else {
            System.err.println("Usage: Summation <integer value>");
        }
    }
}
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
• 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

• Windows API supports thread pools:

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

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

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

    #pragma omp parallel
    {
        /* sequential code */

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

        /* sequential code */

        printf("I am a parallel region.");
    }

    /* sequential code */

    return 0;
}
```

- `#pragma omp parallel`: Create as many threads as there are cores
- `#pragma omp parallel for`: Run for loop in parallel
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

```c
dispatch.queue_t queue = dispatch.get_global_queue
      (DISPATCH_QUEUE_PRIORITY_DEFAULT, 0);

dispatch.async(queue, ^{
    printf("I am a block.");
});
```
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
  – Signal is generated by a particular event
  – Signal is delivered to a process
  – Signal is handled by one of two signal handlers:
    • default
    • 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:

```c
pthread_t tid;

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

...  

/* cancel the thread */
pthread_cancel(tid);
```
Thread Cancellation (Cont.)

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>State</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>Disabled</td>
<td>–</td>
</tr>
<tr>
<td>Deferred</td>
<td>Enabled</td>
<td>Deferred</td>
</tr>
<tr>
<td>Asynchronous</td>
<td>Enabled</td>
<td>Asynchronous</td>
</tr>
</tbody>
</table>

- 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_testcasel()`
    - 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)
- 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 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
• 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 (Cont.)

• 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

- ETHREAD
  - thread start address
  - pointer to parent process

- KTHREAD
  - scheduling and synchronization information
  - kernel stack

- TEB
  - thread identifier
  - user stack
  - thread-local storage

kernel space | user space
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

<table>
<thead>
<tr>
<th>flag</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLONE_FS</td>
<td>File-system information is shared.</td>
</tr>
<tr>
<td>CLONE_VM</td>
<td>The same memory space is shared.</td>
</tr>
<tr>
<td>CLONE_SIGHAND</td>
<td>Signal handlers are shared.</td>
</tr>
<tr>
<td>CLONE_FILES</td>
<td>The set of open files is shared.</td>
</tr>
</tbody>
</table>

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