CS370 Operating Systems

Colorado State University
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Spring 2022 Lecture 7
Threads

Slides based on
- Text by Silberschatz, Galvin, Gagne
- Various sources
Today

• Threads
• Amdahl’s law
• Kernel support for threads
• Pthreads
• Java Threads
• Implicit threading
**UNIX pipe example**

**Parent Process:**
```
#define READ_END 0
#define WRITE_END 1
int fd[2];
create the pipe:
    if (pipe(fd) == -1) {
        fprintf(stderr,"Pipe failed");
        return 1;
    }
fork a child process:
    pid = fork();
parent process:
    close(fd[READ_END]); /* close the unused end of the pipe */
    write(fd[WRITE_END], write_msg, strlen(write_msg)+1); /* write to the pipe */
    close(fd[WRITE_END]); /* close the write end of the pipe */
child process:
    close(fd[WRITE_END]); /* close the unused end of the pipe */
    read(fd[READ_END], read_msg, BUFFER_SIZE); /* read from the pipe */
    printf("child read %s\n",read_msg);
    close(fd[READ_END]); /* close the write end of the pipe */
```
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Chapter 4: Threads

Objectives:
- Thread—basis of multithreaded systems
- APIs for the Pthreads and Java thread libraries
- implicit threading, multithreaded programming
- OS support for threads
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
  - Extra hardware needed for parallel execution

- **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:
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**
  - *e.g. hyper-threading*
- Oracle SPARC T4 with 8 cores, and 8 hardware threads per core (total 64 threads)
- AMD Ryzen 7 with 4 cores and 8 threads
Single and Multithreaded Processes

![Diagram showing single-threaded and multithreaded processes]

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

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

- Thread
Process vs Thread

• All threads in a process have same address space (text, data, open files, signals etc.), same global variables

• Each thread has its own
  – Thread ID
  – Program counter
  – Registers
  – Stack: execution trail, local variables
  – State (running, ready, blocked, terminated)

• Thread is also a schedulable entity
Identifies performance gains from adding additional cores to an application that has both serial and parallel components.

- **S** is serial portion (as a fraction) that cannot be broken into parallel operations.
- Some things can possibly be done in parallel.
- **N** processing cores

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

- Example: if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of
  \[
  1/(0.25 + 0.75/2) = 1.6 \text{ times}
  \]
- As **N** approaches infinity, speedup approaches \(1/S\)

Serial portion of an application has disproportionate effect on performance gained by adding additional cores
Amdahls law: ordinary life example.

Which of the two option is faster?

- Person A cooks, person B eats and then Person C eats.
- Person A cooks, then both person B and person C eat at the same time.
User Threads and Kernel Threads

- **User threads** - management done by user-level threads library
- Three main thread libraries:
  - POSIX **Pthreads**
  - Windows threads
  - Java threads
- **Kernel threads** - Supported by the Kernel
  - Examples – virtually all general-purpose operating systems, including:
    - Windows
    - Linux
    - Mac OS X
Multithreading Models

How do kernel threads support user process threads?

- Many-to-One: Many user-level threads mapped to single kernel thread (thread library in user space (older model))
- One-to-One: (now common)
- Many-to-Many: Allows many user level threads to be mapped to smaller or equal number of kernel threads (older systems)
Many-to-One

- Many user-level threads mapped to single kernel thread (thread library in user space older model)
- 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 for Java 1996
  - GNU Portable Threads 2006
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 smaller or equal number of kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9 (2002-3)
- Windows with the "ThreadFiber" package (NT/2000)
Two-level Model

• Similar to M:M, except that it allows a user thread to be **bound** to a kernel thread

• Examples
  – IRIX -2006
  – 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
POSIX Pthreads

- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization (1991)
- **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)
Some Pthread management functions

<table>
<thead>
<tr>
<th>POSIX function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pthread_cancel</td>
<td>Terminate a thread</td>
</tr>
<tr>
<td>pthread_create</td>
<td>Create a thread</td>
</tr>
<tr>
<td>pthread_detach</td>
<td>Set thread to release resources</td>
</tr>
<tr>
<td>pthread_exit</td>
<td>Exit a thread without exiting process</td>
</tr>
<tr>
<td>pthread_kill</td>
<td>Send a signal to a thread</td>
</tr>
<tr>
<td>pthread_join</td>
<td>Wait for a thread</td>
</tr>
<tr>
<td>pthread_self</td>
<td>Find out own thread ID</td>
</tr>
</tbody>
</table>

• Return 0 if successful
POSIX: Thread creation  

`pthread_create()`

- Automatically makes the thread runnable without a start operation
- Takes 3 parameters:
  - Points to ID of newly created thread
  - Attributes for the thread
    - Stack size, scheduling information, etc.
  - Name of function that the thread calls when it begins execution with argument

```c
/* create the thread */
pthread_create(&tid, &attr, runner, argv[1]);
```
POSIX: Detaching and Joining

- **pthread_detach()**
  - Sets internal options to specify that storage for thread can be reclaimed when it exits
  - 1 parameter: Thread ID of the thread to detach
  - Undetached threads don’t release resources until
    - Another thread calls `pthread_join` for them
    - Or the whole process exits

- **pthread_join**
  - Takes ID of the thread to wait for
  - Suspends calling thread till target terminates
  - Similar to `waitpid` at the process level
  `pthread_join(tid, NULL);`
POSIX: Exiting and cancellation

• If a process calls exit, **all** threads terminate
• Call to `pthread_exit` causes only the calling thread to terminate

`pthread_exit(0)`

• Threads can force other threads to return through a **cancellation** mechanism
  – `pthread_cancel()`: takes thread ID of target
  – Actual cancellation depends on *type* and *state* of thread
• This process will have two threads
  – Initial/main thread to execute the main() function. It creates a new thread and waits for it to finish.
  – A new thread that runs function runner()
    • It will get a parameter, an integer, and will compute the sum of all integers from 1 to that number.
    • New thread leaves the result in a global variable sum.
  – The main thread prints the result.
#include <pthread.h>
#include <stdio.h>

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

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

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

  if (argc != 2) {
    fprintf(stderr,"usage: a.out <integer value>\n");
    /*exit(1);*/
    return -1;
  }

  if (atoi(argv[1]) < 0) {
    fprintf(stderr,"Argument %d must be non-negative\n",atoi(argv[1]));
    /*exit(1);*/
    return -1;
  }

  return 0;
}

thread runner will perform summation of integers 1, 2, ..n
Pthreads Example Pt 2

/* get the default attributes */
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 begin control in this function */
void *runner(void *param)
{
int i, upper = atoi(param);
sum = 0;
    if (upper > 0) {
        for (i = 1; i <= upper; i++)
            sum += i;
    }
    pthread_exit(0);
}
/* create the threads */
for (i = 0; i < NUM_THREADS; i++)
    pthread_create(&tid[i], &attr, runner, NULL);

/* now join on each thread */
for (i = 0; i < NUM_THREADS; i++)
    pthread_join(tid[i], NULL);
}

/* Each thread will begin control in this function */

void *runner(void *param)
{
    /* do some work ... */
    pthread_exit(0);
}

/* create the threads */
for (i = 0; i < NUM_THREADS; i++)
    pthread_create(&tid[i], &attr, runner, NULL);

/* now join on each thread */
for (i = 0; i < NUM_THREADS; i++)
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    pthread_join(tid[i], NULL);
}

/* Each thread will begin control in this function */

void *runner(void *param)
{
    /* do some work ... */
    pthread_exit(0);
}
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
    - Override its run() method
  - More commonly, implementing the Runnable interface
    1. Has 1 method run()
    2. Create new Thread class by passing a Runnable object to its constructor
    3. start() method creates a new thread by calling the run() method.
- new features available in java.util.concurrent package

Runnable interface is defined by

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

- **New**
  - start()

- **Runnable**
  - run() method exits or stop()
  - sleep() done, i/o complete, lock available, resume(), notify() or notifyAll()

- **Running**
  - sleep(), block on I/O, wait for lock, suspend(), wait()

- **Non Runnable (Blocked)**

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[link: https://www.javatpoint.com/life-cycle-of-a-thread]
Java version of a multithreaded program that computes summation of a non-negative integer.
This program creates a separate thread by implementing the Runnable interface.

```java
class Sum {
    private int sum;

    public int get() {
        return sum;
    }

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

Program Overall Structure
```
class sum {
    }
class summation implements runnable {
    ...
    public void run() { .. }
}
Public class Driver {
    ....
    public static void main(String[] args) {
        Thread worker = new Thread(new summation( ... worker.start();
        try {
            worker.join(); ....
        }
```
class Summation implements Runnable
{
    private int upper;
    private Sum sumValue;

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

    //this method runs as a separate thread
    public void run() {
        int sum = 0;
        for (int i = 0; i <= upper; i++)
            sum += i;
        sumValue.set(sum);
    }
}
Ex: Using Java Threads (3/3)

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

        Sum sumObject = new Sum();
        int upper = Integer.parseInt(args[0]);

        Thread worker = new Thread(new Summation(upper, sumObject));
        worker.start();
        try {
            worker.join();
        } catch (InterruptedException ie) {
        }
        System.out.println("The sum of " + upper + " is " + sumObject.get());
    }
}
```
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
Implicit Threading\textsuperscript{1}: 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
- Posix thread pools
- Windows API supports thread pools.
Implicit Threading2: 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
#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

Compile using `gcc -fopenmp openmp.c`

```c
#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;
}
```

Self exercise 3, 4 available now.
Implicit Threading 3: 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
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
Semantics of fork() and exec()

• Does fork() duplicate only the calling thread or all threads?
  – Some UNIXes have two versions of fork
    – 1. when exec() will replace the entire process, dup just that thread
    – 2. duplicate all threads
• exec() usually works as normal – replace the running process including all threads
• **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
• Where should a signal be delivered for multi-threaded process?
  – 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>

- A thread’s cancellation type (mode) and state can be set.
- 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 (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)
  - Ex: Each transaction has a thread and a transaction identifier is needed.

- 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
Is complexity always good?

• Is something that is
  – More advanced
  – More complex
Generally better?