CS 333
Introduction to Operating Systems

Class 3 - Threads & Concurrency

Jonathan Walpole
Computer Science
Portland State University
Threads

- Processes have the following components:
  - an address space
  - a collection of operating system state
  - a CPU context ... or thread of control

- On multiprocessor systems, with several CPUs, it would make sense for a process to have several CPU contexts (threads of control)

- Multiple threads of control could run in the same address space on a single CPU system too!
  - “thread of control” and “address space” are orthogonal concepts
Threads

- Threads share a process address space with zero or more other threads

- Threads have their own
  - PC, SP, register state etc
  - stack

- What other OS state should be private to threads?

- A traditional process can be viewed as an address space with a single thread
Single thread state within a process

User Address Space

stack
- routine1
  - var1()
  - var2()

text
- main()
- routine1()
- routine2()

data
- arrayA
- arrayB

heap

Stack Pointer
- Prgm. Counter
- Registers

Process ID
- Group ID
- User ID

Files
- Locks
- Sockets
Multiple threads in an address space

```
Thread 2  
stack    
routine2() var1  
       var2  
       var3  

Thread 1  
stack    
routine1() var1  
       var2  

main()  
routine1()  
routine2()  

...  

text    
data    
arrayA  
arrayB  

heap    

User Address Space

Stack Pointer
Prgrm. Counter
Registers

Stack Pointer
Prgrm. Counter
Registers

Process ID
User ID
Group ID

Files
Locks
Sockets
```
What is a thread?

- A thread executes a stream of instructions
  - an abstraction for control-flow
- Practically, it is a processor context and stack
  - Allocated a CPU by a scheduler
  - Executes in the context of a memory address space
Summary of private per-thread state

- Stack (local variables)
- Stack pointer
- Registers
- Scheduling properties (i.e., priority)
- Set of pending and blocked signals
- Other thread specific data
Shared state among threads

- Open files, sockets, locks
- User ID, group ID, process/task ID
- Address space
  - Text
  - Data (off-stack global variables)
  - Heap (dynamic data)
- Changes made to shared state by one thread will be visible to the others
  - Reading and writing memory locations requires synchronization! ... a major topic for later ...
Independent execution of threads

Each thread has its own stack
How do you program using threads?

- Split program into routines to execute in parallel
  - True or pseudo (interleaved) parallelism
Why program using threads?

- Utilize multiple CPU's concurrently
- Low cost communication via shared memory
- Overlap computation and blocking on a single CPU
  - Blocking due to I/O
  - Computation and communication
- Handle asynchronous events
Thread usage

A word processor with three threads
Processes versus threads - example

- A WWW process

```
GET / HTTP/1.0
```

HTTPD

disk
Processes versus threads - example

- A WWW process

Why is this not a good web server design?
Processes versus threads - example

- A WWW process

```
GET / HTTP/1.0
```

![Diagram showing processes versus threads example](image)
Processes versus threads - example

- A WWW process

```
GET / HTTP/1.0
HTTPD
GET / HTTP/1.0
```

disk
Processes versus threads - example

- A WWW process

HTTPD

GET / HTTP/1.0

GET / HTTP/1.0

GET / HTTP/1.0

GET / HTTP/1.0

disk
Threads in a web server

A multithreaded web server
Thread usage

- Rough outline of code for previous slide
  (a) Dispatcher thread
  (b) Worker thread
# System structuring options

<table>
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<tr>
<th>Characteristics</th>
<th>Model</th>
<th>Characteristics</th>
</tr>
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<td>Multi-threaded</td>
<td>Threads</td>
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<tr>
<td>Single-threaded</td>
<td>Threads</td>
<td>Single-threaded</td>
</tr>
<tr>
<td>Finite state machine</td>
<td>Threads</td>
<td>Finite state machine</td>
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</tbody>
</table>

**Three ways to construct a server**
Common thread programming models

- **Manager/worker**
  - Manager thread handles I/O and assigns work to worker threads
  - Worker threads may be created dynamically, or allocated from a thread-pool

- **Peer**
  - Like manager worker, but manager participates in the work

- **Pipeline**
  - Each thread handles a different stage of an assembly line
  - Threads hand work off to each other in a producer-consumer relationship
What does a typical thread API look like?

- POSIX standard threads (Pthreads)
- First thread exists in main(), typically creates the others

- `pthread_create (thread, attr, start_routine, arg)`
  - Returns new thread ID in "thread"
  - Executes routine specified by "start_routine" with argument specified by "arg"
  - Exits on return from routine or when told explicitly
Thread API (continued)

- **pthread_exit (status)**
  - Terminates the thread and returns “status” to any joining thread

- **pthread_join (threadid, status)**
  - Blocks the calling thread until thread specified by “threadid” terminates
  - Return status from pthread_exit is passed in “status”
  - One way of synchronizing between threads

- **pthread_yield ()**
  - Thread gives up the CPU and enters the run queue
Using create, join and exit primitives
An example Pthreads program

```c
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

void *PrintHello(void *threadid) {
  printf("%d: Hello World!\n", threadid);
  pthread_exit(NULL);
}

int main (int argc, char *argv[]) {
  pthread_t threads[NUM_THREADS];
  int rc, t;
  for(t=0; t<NUM_THREADS; t++) {
    printf("Creating thread %d\n", t);
    rc = pthread_create(&threads[t], NULL, PrintHello, (void *)t);
    if (rc) {
      printf("ERROR: return code from pthread_create() is %d\n", rc);
      exit(-1);
    }
  }
  pthread_exit(NULL);
}
```

Program Output

Creating thread 0
Creating thread 1
0: Hello World!
1: Hello World!
Creating thread 2
Creating thread 3
2: Hello World!
3: Hello World!
Creating thread 4
4: Hello World!

For more examples see: http://www.llnl.gov/computing/tutorials/pthreads
Pros & cons of threads

- **Pros**
  - Overlap I/O with computation!
  - Cheaper context switches
  - Better mapping to shared memory multiprocessors

- **Cons**
  - Potential thread interactions
  - Complexity of debugging
  - Complexity of multi-threaded programming
  - Backwards compatibility with existing code
Making single-threaded code multithreaded

Conflicts between threads over the use of a global variable
Making single-threaded code multithreaded

Threads can have private global variables
User-level threads

- Threads can be implemented in the OS or at user level
- User level thread implementations
  - thread scheduler runs as user code
  - manages thread contexts in user space
  - OS sees only a traditional process
Kernel-level threads

The thread switching code is in the kernel
User-level threads package

The thread switching code is in user space
User-level threads

- **Advantages**
  - cheap context switch costs!
  - User-programmable scheduling policy

- **Disadvantages**
  - How to deal with blocking system calls!
  - How to overlap I/O and computation!
Hybrid thread implementations

Multiplexing user-level threads onto kernel-level threads
Scheduler activations

- **Goal** – mimic functionality of kernel threads
  - gain performance of user space threads

- **The idea** – kernel upcalls to user-level thread scheduling code when it handles a blocking system call or page fault
  - user level thread scheduler can choose to run a different thread rather than blocking
  - kernel upcalls when system call or page fault returns

- **Kernel assigns virtual processors to each process (which contains a user level thread scheduler)**
  - lets user level thread scheduler allocate threads to processors

- **Problem**: relies on kernel (lower layer) calling procedures in user space (higher layer)
Concurrent programming

Assumptions:
- Two or more threads (or processes)
- Each executes in (pseudo) parallel and can’t predict exact running speeds
- The threads can interact via access to a shared variable

Example:
- One thread writes a variable
- The other thread reads from the same variable

Problem:
- The order of READs and WRITEs can make a difference!!!
Race conditions

- **What is a race condition?**
  - two or more processes have an inconsistent view of a shared memory region (I.e., a variable)

- **Why do race conditions occur?**
  - values of memory locations replicated in registers during execution
  - context switches at arbitrary times during execution
  - processes can see “stale” memory values in registers
Counter increment race condition

- Incrementing a counter (load, increment, store)
- Context switch can occur after load and before increment!
Race Conditions

- **Race condition:** whenever the output depends on the precise execution order of the processes!!!

- **What solutions can we apply?**
  - prevent context switches by preventing interrupts
  - make threads coordinate with each other to ensure mutual exclusion in accessing critical sections of code
Mutual exclusion conditions

- No two processes simultaneously in critical section
- No assumptions made about speeds or numbers of CPUs
- No process running outside its critical section may block another process
- No process must wait forever to enter its critical section
Critical sections with mutual exclusion
How can we enforce mutual exclusion?

- What about using a binary “lock” variable in memory and having threads check it and set it before entry to critical regions?

- Solves the problem of exclusive access to shared data.
  - Expresses intention to enter critical section
  - Acquiring a lock prevents concurrent access

- Assumption:
  - Every thread sets lock before accessing shared data!
  - Every thread releases the lock after it is done!
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Free

Lock
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Free

Lock

Lock
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Set

Lock

Lock
Acquiring and releasing locks
Acquiring and releasing locks

Thread A

Thread B

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Thread B

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Set

Lock

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Thread A

Thread B

Thread C

Thread D

Set

Lock

Lock

Lock

Lock
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Set

Unlock

Lock

Lock

Lock
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Set

Lock

Unlock

Lock

Lock

Lock
Acquiring and releasing locks
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Free

Lock

Lock

Lock

Lock
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Set

Lock

Lock

Lock

Lock
Acquiring and releasing locks

- Thread A
- Thread B
- Thread C
- Thread D

![Diagram showing lock acquisition and release among threads.](Image)
Acquiring and releasing locks

Thread A

Thread B

Thread C

Thread D

Set

Lock

Lock

Lock
Mutex locks

- An abstract data type
- Used for synchronization and mutual exclusion
- The “mutex” is either:
  - Locked ("the lock is held")
  - Unlocked ("the lock is free")
 Mutex lock operations

- **Lock** (*mutex*)
  - Acquire the lock, if it is free
  - If the lock is not free, then wait until it can be acquired

- **Unlock** (*mutex*)
  - Release the lock
  - If there are waiting threads, then wake up one of them

- Both **Lock** and **Unlock** are assumed to be **atomic!!!**
  - A kernel implementation can ensure atomicity
An Example using a Mutex

Shared data:

Mutex myLock;

1 repeat
2 \textbf{Lock}(\textit{myLock});
3 \textbf{critical section}
4 \textbf{Unlock}(\textit{myLock});
5 \textbf{remainder section}
6 until FALSE

1 repeat
2 \textbf{Lock}(\textit{myLock});
3 \textbf{critical section}
4 \textbf{Unlock}(\textit{myLock});
5 \textbf{remainder section}
6 until FALSE
But how can we implement a mutex lock?

- Does a binary “lock” variable in memory work?

- Many computers have *some limited* hardware support for setting locks
  - “Atomic” Test and Set Lock instruction
  - “Atomic” compare and swap operation

- Can be used to implement “Mutex” locks
Test-and-set-lock instruction (TSL, tset)

- A lock is a single word variable with two values
  - 0 = FALSE = not locked
  - 1 = TRUE = locked

- Test and set does the following atomically:
  - Get the (old) value
  - Set the lock to TRUE
  - Return the old value

If the returned value was FALSE...
   Then you got the lock!!!
If the returned value was TRUE...
   Then someone else has the lock
   (so try again later)
Test and set lock

FALSE

Lock
Test and set lock

P1

FALSE

Lock
Test and set lock

FALSE = Lock Available!!

P1

FALSE

Lock
Test and set lock

P1

FALSE

TRUE

Lock
Test and set lock

P1

FALSE

TRUE

Lock
Test and set lock
Test and set lock
Test and set lock
Test and set lock

P1

P2

P3

P4

FALSE

Lock

TRUE

TRUE

TRUE

TRUE

TRUE

TRUE

TRUE

TRUE
Test and set lock
Test and set lock
Test and set lock
Critical section entry code with TSL

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>repeat</td>
</tr>
<tr>
<td>2</td>
<td>while(TSL(lock))</td>
</tr>
<tr>
<td>3</td>
<td>no-op;</td>
</tr>
<tr>
<td>4</td>
<td>critical section</td>
</tr>
<tr>
<td>5</td>
<td>Lock = FALSE;</td>
</tr>
<tr>
<td>6</td>
<td>remainder section</td>
</tr>
<tr>
<td>7</td>
<td>until FALSE</td>
</tr>
</tbody>
</table>

- Guarantees that only one thread at a time will enter its critical section
- Note that processes are **busy** while waiting
  - Spin locks
Busy waiting

- Also called polling or spinning
  - The thread consumes CPU cycles to evaluate when lock becomes free!!!

- Shortcoming on a single CPU system...
  - A busy-waiting thread can prevent the lock holder from running & completing its critical section & releasing the lock!
  - Better: Block instead of busy wait!
Quiz

- What is the difference between a program and a process?
- Is the Operating System a program?
- Is the Operating System a process?
- What is the difference between processes and threads?
- What tasks are involved in switching the CPU from one process to another?
  - Why is it called a context switch?
- What tasks are involved in switching the CPU from one thread to another?
  - Why are threads “lightweight”?