THREADS & SYNCHRONIZATION

ISA 563: Fundamentals of Systems Programming

Major Thread Environments

- UNIX: pthreads library
- Java: Thread class, Runnable interface
- Intel Thread Building Blocks Library
  - http://www.threadingbuildingblocks.org/documentation.php

Reasons to Use Threads

- Threads typically involve less overhead (memory & CPU time) than a full process
  - All threads "within" a process share the same memory as the containing process and each other
  - The overhead of "fork(2)" is avoided
  - Context switching (time for OS to "give" the CPU to another process) between multiple processes is avoided

- Threads can more naturally reflect independent but related subtasks of an algorithm or process
  - Potential for parallel execution & some speedup

High Level: What is a Thread?

- Threads represent an independent control flow within a process
- How threads are implemented often depends on the underlying thread library and operating system
- POSIX defines a standard thread API to manage the lifecycle of a thread as well as synchronization primitives

Logical Thread Content

- Threads typically contain the following state:
  - A thread ID *tid*
  - Scheduling data: policy & priority
  - A set of registers (i.e., CPU state), including:
    - A program counter (keep track of which instruction the thread is executing)
    - A stack (independent of the process's stack and any other threads within the process)
  - Their own *errno*
  - Their own signal mask set

Mapping Threads to Code

- Threads execute code independently; more than 1 thread can simultaneously execute the same assembly instructions

- In other words, source code doesn't necessarily "belong" to any one thread
    - The association of code to threads can change dynamically during runtime

Major Issue: Synchronized Access

- Two or more threads, in executing the same program statements simultaneously, might access (i.e., read or write) the same data items
  - Because thread execution ordering is unpredictable (just like process scheduling), consistency is unpredictable
  - Program correctness is then questionable
  - Thread APIs (pthreads, Java's Thread object and synchronization primitives) often provide ways to control or synchronize access to shared data

Two Threads Sorting Same Data

Thead 1: shell_sort(data, len)

```
for(gap=len/2;
      gap>0;
      gap/=2)
  for(i=gap;
       i<len;
       i++)
   for(j=i-gap;
        j>=0 &&
    data[j]>data[+gap];
    j-=gap)
    swap(data[i], data[i+gap]);
```

EIP of thread 1

Thread 2: shell_sort(data, len)

```
for(gap=len/2;
      gap>0;
      gap/=2)
  for(i=gap;
       i<len;
       i++)
   for(j=i-gap;
        j>=0 &&
    data[j]>data[+gap];
        j-=gap)
    swap(data[i], data[i+gap]);
```

EIP of thread 2

Solution? Locking and Synchronization

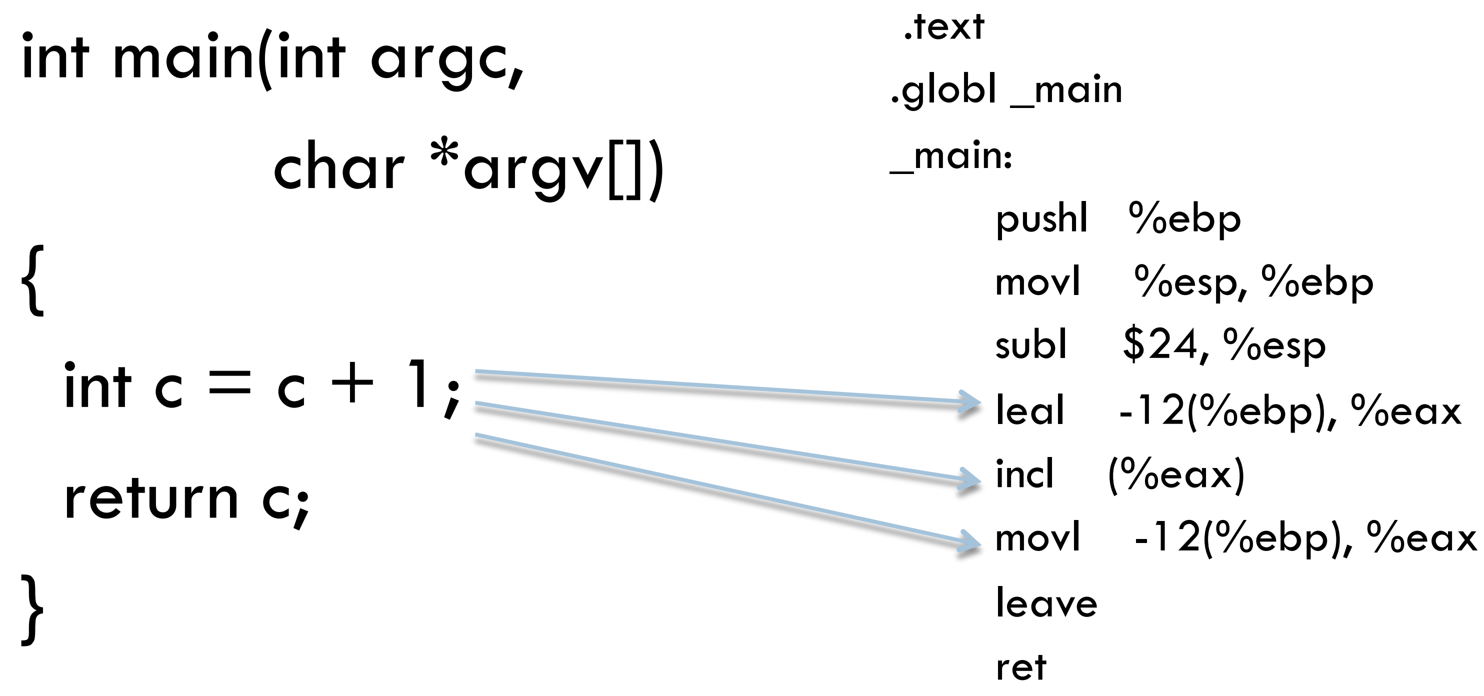
- The main idea is to provide atomic operations that govern permission to enter a critical section
  - **Atomic operations** are operations that execute in a single machine clock cycle and cannot be interrupted at any point in their execution
  - A **critical section** is a section of code that manipulates shared data items and must be made thread-safe in order to ensure program correctness
  - Specifics of how pthread library does it later…

Background: Atomic Operations

- A single line of C code corresponds to multiple assembly (machine) instructions

- Even a single machine instruction may not execute in 1 clock cycle!

Mapping C to ASM Instructions



C Code

```
int main(int argc,
            char *argv[])
{
  int c = c + 1;
  return c;
}
```

ASM Code

```
 .text
.globl _main
_main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        leal    -12(%ebp), %eax
        incl    (%eax)
        movl    -12(%ebp), %eax
        leave
        ret
```

Mapping ASM to Clock Cycles

ASM Code

```
 .text
.globl _main
_main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        leal    -12(%ebp), %eax
        incl    (%eax)
        movl    -12(%ebp), %eax
        leave
        ret
```

Instruction Mneumonic

LEA: Load Effective Address: 2 cycles

INC: Increment by 1: 1 or 2 cycles

MOV: Copy 2nd operand to 1st operand: cycles vary

Highlights of Security Issues

- Privilege Separation between threads
- Information leaks & covert channels
- TOCTTOU (time-of-check-to-time-of-use) errors
- Memory leaks or double-free errors due to mismanagement of reference counters
- DoS due to deadlock (internal mismanagement of control paths leading to lock-acquiring mis-ordering)

Operating with Threads

Creating Threads

Tracking of Thread ID

Terminating & Joining Threads

Comparing Process & Thread Lifecycles

Process Functions	**Thread Functions**
fork(2)	pthread_create
atexit(2)	pthread_cleanup_push
_exit(2)	pthread_exit
waitpid(2)	pthread_join
getpid(2)	pthread_self

Thread Creation

The ‘pthread_create(3)’ function is a pthread library function that instructs the operating system to create a thread in the current process’s context

Operating Systems can do this (i.e., map threads to OS processes) in many ways

Linux uses clone(), so 1 thread per process

Thread Creation & Running

- Threads do not follow the fork/exec pattern for Unix processes

- Instead, when they are created, they are explicitly assigned a section of code to begin executing via the 3rd argument of pthread_create, a function pointer

Thread Identification

- int pthread_equal(pthread_t tid1, pthread_t tid2);

- pthread_t pthread_self(void);

Why a function to compare pthread IDs?

Because the pthread_t type can be a structure

(not necessarily an integer like pid_t)

Terminating Threads

- Use pthread_exit: extinguish current thread
- Use pthread_join: extinguish target thread (i.e., join with caller)
- Use pthread_cancel to request that another target thread be extinguished
- Threads can register shutdown hooks via:
  - Using pthread_cleanup_push()
  - Using pthread_cleanup_pop()

Using pthread_exit

- Allows a thread to terminate itself
- Can pass back a pointer to a return value:
  - `pthread_exit((void*)RETURN_CODE);`
- Return value can also be a structure
  - But be careful that it is a valid pointer!
  - For example, variables local to the thread stack may be destroyed by the time the caller uses the thread's return structure value
- See Figure 11.4, page 362..364

Thread Shutdown Hooks

- Similar to atexit(3) process exit handlers
- Calls to pthread_cleanup_push and pthread_cleanup_pop must match in the source code

- These might be implemented as macros

- Figure 11.5 in APUE

Synchronization Mechanisms

Mutexes

Reader-writer locks (shared-exclusive locks)

Condition variables

Synchronization with Mutexes

- **Mut**ual **Ex**clusion: **mutex**
  - A property whereby a resource is available to only 1 thread at a time. A mutex is a data item that represents a ‘lock’ on a resource
- Threads must acquire the mutex before manipulating the resource
  - This is a convention only: the OS and hardware do not enforce access on a data item --- the calling thread must be cooperative and include the calls to the mutex acquisition routines!

Caveats

- Threads can ignore mutexes and just access the data
- Threads can race to acquire the mutex itself
- Ordering of mutex acquisition and release must be the same across potentially many code paths; deadlock can occur when an infrequently-exercised code path (and thus series of mutex acquisitions) is executed by multiple threads

Using pthread Mutex Variables

- Static Allocation:

  pthread_mutex_t mlock = PTHREAD_MUTEX_INITIALIZER;

- Dynamic Allocation:

  Use pthread_mutex_init after malloc of a pthread_mutex_t pointer

  Must use pthread_mutex_destroy before freeing mutex pointer

- Lock / Unlock

```
pthread_mutex_lock(&mlock);
//critical section, update shared data
pthread_mutex_unlock(&mlock);
```

Can't Afford to Block?

- Use pthread_mutex_trylock
  - The calling thread can return without block from this function
  - It can then decide whether to try again, essentially looping on the mutex, or continue on some other processing path

Reader-Writer Locks

- A better name is “shared-exclusive”
  - Three modes of access:
    - “read”: multiple threads can read this resource
    - “write”: a single thread locks resource to write to it
    - “open”: unlocked
- Finer-grained than unlocked/locked of mutexes
  - But has potential to starve writers if a high rate of readers occurs; some implementations handle this
  - Suitable for data structures that are read more often than they are updated

Condition Variables

- Customize locking based on state of the shared data
- When condition is satisfied, a signal is sent to interested threads

Summary: Take-Home Message

- Threads provide a mechanism for allowing a single, monolithic piece of source code to accomplish multiple independent or dependent subtasks concurrently

- Concurrency introduces challenges with regards to consistency of critical data items
  - Synchronization primitives provide a means to protect critical sections of code, but the burden rests on the programmer to use them correctly

Summary: Things to Consider

- Why use threads instead of fork?
- Do threads guarantee mutual exclusion?
- How would you find bugs (e.g., TOCTTOU) in multi-threaded code?
- Do threads **always** require locking?
- Can a single thread cause the entire process to terminate?