ECE 454
Computer Systems Programming

Threads and Synchronization

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Overall Progress of the Course

• What we have learnt so far: improving sequential performance
  • CPU architecture
  • Compiler optimization
  • Optimizations for processor caches
  • Virtual memory, dynamic memory performance

• Next: improving performance by parallelization
  • Single machine parallelization
    • Using threads and processes on a single machine
  • Multi-machine parallelization
    • Using modern, data-intensive distributed computing
Contents

- Threads and processes
- Posix threads
- Mutual exclusion
- Synchronization
Threads and Processes
Parallel Processing with Processes

- E.g., web server or any other online service

- Using just one process is problematic
  - Client request arrives
  - Servicing request may require reading data from disk
    - Process blocks waiting for IO
    - Other requests cannot be serviced while blocked

- Idea: use multiple processes to service requests
  - Concurrently
    - When a process blocks, another process can run on the same core
  - Parallel
    - Multiple processes can run simultaneously on different cores
Fork(): OS sys call to create new process. Address space of child is an exact copy of parent (same data, same code, same PC, except Fork() of child returns 0; Fork() of parent returns pid of child).
Sample Server

```c
int main(int argc, char **argv) {
    int listenfd, connfd;
    struct sock_addr_storage client_addr;

    listenfd = open_listenfd(argv[1]);
    while (1) {
        socklen_t clientlen = sizeof(struct sock_addr_storage);
        connfd = Accept(listenfd, &client_addr, &clientlen);
        if (Fork() == 0) { // I am a child process
            close(listenfd);
            Read_and_Process_Request(connfd);
            close(connfd);
            exit();
        }
        close(connfd);
    }
    close(connfd);
}
```
Interprocess Communications (IPC)

- Above program requires no communication between processes
- But what if we do require communication?
  - Send signals
  - Sockets (TCP/IP connections)
  - Pipes
  - Memory mapped regions (mmap())
    - Access to shared data needs to be synchronized…
      - How?

Mapped region is shared. Writes to region can be read immediately by either process
Process

Process = process context (CPU state) + address space (code, data, and stack) + kernel state

**Process context**
- Data registers
- Condition codes
- Stack pointer (SP)
- Program counter (PC)

**Address space**
- Stack
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data
- Brk
- File descriptor table

**Kernel state**
- Virt. mem. structures
- Brk pointer
- File descriptor table
Performance Overhead in Process Management

- Creating a new process is costly because of all the data structures (process context, address space, kernel state) that must be allocated and initialized

- Communicating between processes is costly because communication goes through the OS
  - Overhead of system calls and copying data
  - Switching between processes is also expensive
    - Why?
Rethinking Processes

• What do cooperating processes share?
  • They share some code and data (address space)
  • They share some privileges, files, sockets, etc. (kernel state)

• What don’t they share?
  • Each process has its own execution state: PC, SP, and registers

• Key idea: Why don’t we separate the concept of a process from its execution state?
  • Process: address space, kernel state
  • Execution state: PC, SP, registers

• Execution state also called thread of control, or thread
Threads: Lightweight Processes

- **Environment (resource)**
- **Execution**

(a) Three processes each with one thread
(b) One process with three threads
Process with Two Threads

Thread context:
- Data registers
- Condition codes
- Stack pointer (SP)
- Program counter (PC)

Address space:
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data

Kernel state:
- Virtual memory structures
- BRK pointer
- File descriptor table

Thread context:
- Data registers
- Condition codes
- Stack pointer (SP)
- Program counter (PC)

Stack pointer (SP)
Threads vs. Processes

• Similarities
  • Each has its own logical control flow
  • Each runs independently of (concurrently with) others

• Differences
  • Threads share code and data, processes (typically) do not
  • Threads are much less expensive than processes
    • Process control (creating and destroying processes) is more expensive than thread control
    • Process context switch is much more expensive than for thread switch
Pros and Cons of Thread-Based Designs

• Pros
  • Easy to share data structures between threads
    • e.g., logging information, file cache
  • Threads are more efficient than processes
    • E.g., on Intel 2.6 GHz Xeon E5-2670:
      • Fork: 162 usecs
      • Thread creation: 18 usecs

• Cons
  • Unintentional sharing can cause subtle, hard-to-reproduce errors!
  • The ease with which data can be shared is both the greatest strength and the greatest weakness of threads
Posix Threads
Posix Threads (Pthreads) Interface

- Pthreads: Standard interface of ~60 functions that manipulate threads from C programs

- Creating and reaping threads
  - pthread_create(pthread_t *tid, ..., func *f, void *arg)
  - pthread_join(pthread_t tid, void **thread_return)

- Determining your thread ID
  - pthread_self()
### Posix Threads (Pthreads) Interface

- **Terminating threads**
  - `pthread_cancel(pthread_t tid)`
  - `pthread_exit(void *thread_return)`
  - `return` (in primary thread routine terminates the thread)
  - `exit()` (terminates all threads)

- **Synchronizing access to shared variables**
  - Later
Example of Thread Creation

main()

pthread_create(func)

func()
void *func(void *) { ..... }

pthread_t id;
int X;
pthread_create(&id, NULL, func, (void *)&X);
...
pthread_join(id, NULL);   // awaits function to return
...
Example of Thread Creation (contd.)

main()
pthread_create(func)

pthread_join(id)
waits for other thread to complete

func()

return NULL;
/* hello.c - Pthreads "hello, world" program */
#include "csapp.h"

void *thread(void *vargp);

int main() {
    pthread_t tid;
    Pthread_create(&tid, NULL, &thread, NULL);
    Pthread_join(tid, NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    printf("Hello, world!\n");
    return NULL;
}
How to Program with Pthreads

- Decide how to decompose the computation into parallel parts
- Create (and destroy) threads to support that decomposition
- Add synchronization to make sure dependences are satisfied
- Easier said than done!
Example: Matrix Multiply

for(i=0; i<n; i++) {
    for(j=0; j<n; j++) {
        for(k=0; k<n; k++) {
            c[i][j] += a[i][k]*b[k][j];
        }
    }
}

• All i- or j-iterations can be run in parallel

• One option:
  • If we have p cores, assign n/p rows of C matrix to each core
  • Corresponds to partitioning the i-loop
Parallel Matrix Multiply

```c
int n = 1000000000;
int p = 16; // # of cores

int main() {
    pthread_t thread[p];

    for(i=0; i<p; i++) {
        pthread_create(&thread[i], NULL, mmult, (void*) &i);
    }

    for(i=0; i<p; i++)
        pthread_join(thread[i], NULL);
}
```
Matrix Multiply Per Thread

```c
void mmult (void* s) {
    int slice = *((int *)s);

    int from = (slice*n)/p;
    int to = ((slice+1)*n)/p;

    for(i=from; i<to; i++) {
        for(j=0; j<n; j++) {
            for(k=0; k<n; k++)
                c[i][j] += a[i][k]*b[k][j];
        }
    }
}
```
Some Models for Threaded Programs

- Manager / worker
  - Manager performs setup
  - Partitions work, e.g., by request
  - Synchronizes completion
- Pros
  - Simple initial design
- Cons
  - Shared state complicates design, synchronization
  - Easier to make workers stateless by separating state from workers, but then workers need to re-read up-to-date state when they operate on it
  - Hard to enforce job ordering
Some Models for Threaded Programs

- Pipelined execution
  - Execution of a request may be pipelined across multiple processes

- Pros
  - Processes share no state, buffers perform synchronization
    - Each process is simple, written like a single threaded application
    - Each process can be stateful
  - Jobs can be ordered, logged
    - Simplifies tasks like backup, replication

- Cons
  - Code is written in callback style, making it hard to debug
Mutual Exclusion
What is Mutual Exclusion?

- Ensures operations on shared data are performed by only one thread at a time, aka *critical section*
  - Ensured by using locks
  - Helps avoid races
- Does not provide any guarantees on ordering
  - Provided by synchronization (discussed later)
Mutual Exclusion Goals

- Works independent of speed of execution of threads
- Threads outside critical sections don’t block other threads
- Threads trying to enter critical section succeed eventually
- Critical sections are small, allowing better scalability
Mutual Exclusion and Critical Sections

- Lock
- Load X
- Store X
- Unlock

Size of critical section impacts execution time.
Coarse-Grain Locking (a.k.a. Global Lock)

lock
... = A
...
A = ...
unlock

lock
... = A
...
A = ...
unlock

easy 😊
Coarse-Grain Locking
(a.k.a. Global Lock)

lock ...
... = A
A = ...
unlock

lock ...
... = B
B = ...
unlock

easy ☻ but slow ☹️
Fine-Grained Locking

- Lock A
- \( \ldots = A \)
- A = \( \ldots \)
- Unlock A
- Lock B
- \( \ldots = B \)
- B = \( \ldots \)
- Unlock B

Time

Fast ☺ but harder 😞
Contention and Scalability

- **Contention** refers to a lock that is held when another thread tries to acquire it.
- **Scalability** refers to the ability to handle increasing load with a larger system.
- Locking serializes execution of critical sections:
  - Limits ability to use multiple processors, recall Amdahl’s law.
  - Locks that are frequently contended limit scalability.
- Coarse-grained locking increases contention:
  - Causes unnecessary cache misses from coherence protocol.
  - May make performance even worse than single core.
Example 1: Linux Kernel Scalability

- “An Analysis of Linux Scalability to Many Cores” [OSDI’10]
  - Linux 2.6.39 (2011) removed the last instance of big kernel lock

**Figure 3:** MOSBENCH results summary. Each bar shows the ratio of per-core throughput with 48 cores to throughput on one core, with 1.0 indicating perfect scalability. Each pair of bars corresponds to one application before and after our kernel and application modifications.
Example 2: Facebook’s memcached

Big lock to protect shared data structure

Fine-grained, striped lock

“Scaling Memcache at Facebook” [NSDI’13]
“Enhancing the Scalability of Memcached” [Intel@ Developer Zone’12]
Races

• A race occurs when certain thread interleavings lead to incorrect program behavior
  - E.g., program depends on one thread reaching point x before another thread reaches point y, but the program doesn’t enforce this behavior

• A data race occurs when a variable is accessed (read or modified) by multiple threads without any synchronization, and at least one thread modifies the variable
Data Race Example

/* a threaded program with a data race */
int main() {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++)
        pthread_create(&tid[i], NULL, thread, &i);
    for (i = 0; i < N; i++)
        pthread_join(tid[i], NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    int myid = *((int *)vargp);
    printf("Hello from thread %d\n", myid);
}
Output: Why?

$ ./race
Hello from thread 1
Hello from thread 2
Hello from thread 6
Hello from thread 3
Hello from thread 7
Hello from thread 5
Hello from thread 9
Hello from thread 4
Hello from thread 9
Hello from thread 0
Synchronization
What is Synchronization?

• Ensures ordering of events to preserve dependencies
  • Barriers: All threads wait at same point in the program
    • E.g., doing pthread_join for all threads
  • Producer-consumer
    • E.g., Thread A writing a stream of samples, Thread B reading them
  • Condition variables used to wait for an event to occur
Barriers

threads need to be at same program point before continuing
Barriers with Pthreads

• Initialize a barrier with count threads
  
  ```c
  pthread_barrier_t *barrier;
pthread_barrier_init(pthread_barrier_t *barrier,
                    pthread_barrier_attr_t *attr,
                    unsigned int count)
  ```

• Wait for all threads to reach the barrier before continuing
  
  ```c
  pthread_barrier_wait(pthread_barrier_t *barrier)
  ```
Condition Variables with Pthreads

• Requires using locks while condition variables are used

• Create a new condition variable
  
  ```c
  pthread_cont_t *cond;
  pthread_cond_init(pthread_cond_t *cond,
                   pthread_cond_attr *attr)
  ```

• Destroy a condition variable
  
  ```c
  pthread_cond_destroy(pthread_cond_t *cond)
  ```
Condition Variable Synchronization

- Block the calling thread on condition variable cond
  \[
  \text{pthread\_cond\_wait}(\text{pthread\_cond\_t} *\text{cond}, \\
  \text{pthread\_mutex\_t} *\text{mutex})
  \]
  - Atomically unlocks the mutex, waits on cond
  - When cond is signaled, reacquires mutex

- Unblock one thread waiting on cond
  \[
  \text{pthread\_cond\_signal}(\text{pthread\_cond\_t} *\text{cond})
  \]
  - If no thread is waiting, signal does nothing

- Unblock all threads waiting on cond
  \[
  \text{pthread\_cond\_broadcast}(\text{pthread\_cond\_t} *\text{cond})
  \]
  - If no thread waiting, then broadcast does nothing.
Example: Parallelize This Code

```
for(i=1; i<100; i++) {
    a[i] = ...;
    ...; // long code
    ... = a[i-1];
}
```

- Problem:
  - Each iteration depends on the previous iteration
Synchronization with Condition Variable

```c
for( i=...; i<...; i++ ) {
    a[i] = ...;
    signal(e_a[i]);
    ...; // long code
    wait(e_a[i-1]);
    ... = a[i-1];
}
```

**PROBLEM**

* signal does nothing if corresponding *wait* hasn’t already executed
  * i.e., signal gets “lost”

need a cond variable for each iteration

signal is lost if wait hasn’t executed yet

wait waits forever -- deadlock!

```c
... = a[2];
... = a[3];
... = a[4];
```
How to Remember a Signal

```c
signal(i) {
    pthread_mutex_lock(&mutex_rem[i]);
    arrived[i] = 1;    // track that signal(i) has happened
    pthread_cond_signal(&cond[i]);    //signal
    pthread_mutex_unlock(&mutex_rem[i]);
}

wait(i) {
    pthreads_mutex_lock(&mutex_rem[i]);
    if (arrived[i] == 0) // wait only if signal hasn’t happen yet
        pthreads_cond_wait(&cond[i], mutex_rem[i]);
    arrived[i] = 0;  // reset for next time
    pthreads_mutex_unlock(&mutex_rem[i]);
}
```
Synchronization with Semaphores

• Semaphores store state and so wait and signal can happen in either order

```c
for( i=...; i<...; i++ ) {
    a[i] = ...;
    up(e_a[i]);      // similar to signal, increments semaphore
    ...;             // long code
    down(e_a[i-1]);  // similar to wait, decrements semaphore
    ... = a[i-1];
}
```
**Producer-Consumer Problem**

- Threads communicate with each other using a shared buffer of a fixed size (i.e., bounded buffer)
  - One or more producers fill buffer
  - One or more consumers empty buffer
- Two synchronizations conditions
  - Producers wait if the buffer is full
  - Consumers wait if the buffer is empty
Bounded Buffer Implementation

- Implementation uses a circular buffer
  - Producers write at in, increment in, go clockwise
  - Consumers read from out, increment out, go clockwise
  - Number of elements in buffer: count = (in - out + n) % n
    - E.g., count = (6 - 3 + 8) % 8 = 3  // n is 8 since buffer has 8 slots
  - Buffer is full when it has n-1 elements, i.e., count == (n - 1)
  - Buffer is empty when it has no elements, i.e., count == 0

shared variables:
char buf[8]; // 7 usable slots
int in;     // place to write
int out;    // place to read

```
in = 6
out = 3
```
Producer-Consumer with Monitors

Global variables:
buf[n], in, out;
lock l = 0;
cv full; // no initialization
cv empty;

void send(char msg) {
    lock(l);
    while (((in-out+n)%n == n - 1) {
        wait(full, l);
    } // full
    buf[in] = msg;
    in = (in + 1) % n;
    signal(empty, l);
    unlock(l);
}

char receive() {
    lock(l);
    while (in == out) {
        wait(empty, l);
    } // empty
    msg = buf[out];
    out = (out + 1) % n;
    signal(full, l);
    unlock(l);
    return msg;
}

• Why two condition variables?
• Why use “while”, instead of “if”?
Producer-Consumer with Semaphores

Global variables:
buf[n], in, out;
lock l;
sem full = 0; // no full slots
sem empty = n; // all slots are empty

void send(char msg) {
    down(empty);
    lock(l);
    buf[in] = msg;
    in = (in + 1) % n;
    unlock(l);
    up(full);
}

char receive() {
    down(full);
    lock(l);
    msg = buf[out];
    out = (out + 1) % n;
    unlock(l);
    up(empty);
    return msg;
}

• Why two condition variables?
• Why is locking needed?
• Can we switch down(), lock()?