CS 31: Intro to Systems
Other Forms of Synchronization / Thread Patterns

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Agenda

• Classic thread patterns

• Pthreads primitives and examples of other forms of synchronization:
  – Condition variables
  – Barriers
  – RW locks
Common Thread Patterns

- Producer / Consumer (a.k.a. Bounded buffer)
- Thread pool (a.k.a. work queue)
- Thread per client connection
The Producer/Consumer Problem

- Producer produces data, places it in shared buffer
- Consumer consumes data, removes from buffer
- Cooperation: Producer feeds Consumer
  - How does data get from Producer to Consumer?
  - How does Consumer wait for Producer?
Producer/Consumer: Shared Memory

shared int buf[N], in = 0, out = 0;

**Producer**
while (TRUE) {
    buf[in] = Produce ();
    in = (in + 1) % N;
}

**Consumer**
while (TRUE) {
    Consume (buf[out]);
    out = (out + 1) % N;
}

- Data transferred in shared memory buffer.
Producer/Consumer: Shared Memory

shared int buf[N], in = 0, out = 0;

Producer
while (TRUE) {
    buf[in] = Produce ();
    in = (in + 1)%N;
}

Consumer
while (TRUE) {
    Consume (buf[out]);
    out = (out + 1)%N;
}

• Data transferred in shared memory buffer.

• Is there a problem with this code?
  A. Yes, this is broken.
  B. No, this ought to be fine.
Adding Semaphores

shared int buf[N], in = 0, out = 0;
shared sem filledslots = 0, emptyslots = N;

<table>
<thead>
<tr>
<th>Producer</th>
<th>Consumer</th>
</tr>
</thead>
<tbody>
<tr>
<td>while (TRUE) {</td>
<td>while (TRUE) {</td>
</tr>
<tr>
<td>wait (X);</td>
<td>wait (Z);</td>
</tr>
<tr>
<td>buf[in] = Produce ();</td>
<td>Consume (buf[out]);</td>
</tr>
<tr>
<td>in = (in + 1)%N;</td>
<td>out = (out + 1)%N;</td>
</tr>
<tr>
<td>signal (Y);</td>
<td>signal (W);</td>
</tr>
<tr>
<td>}</td>
<td>}</td>
</tr>
</tbody>
</table>

• Recall semaphores:
  – wait(): decrement sem and block if sem value < 0
  – signal(): increment sem and unblock a waiting process (if any)
Suppose we now have two semaphores to protect our array. Where do we use them?

```c
shared int buf[N], in = 0, out = 0;
shared sem filledslots = 0, emptyslots = N;

Producer
while (TRUE) {
    wait (X);
    buf[in] = Produce ();
    in = (in + 1)%N;
    signal (Y);
}

Consumer
while (TRUE) {
    wait (Z);
    Consume (buf[out]);
    out = (out + 1)%N;
    signal (W);
}
```

<table>
<thead>
<tr>
<th>Answer choice</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>emptyslots</td>
<td>emptyslots</td>
<td>filledslots</td>
<td>filledslots</td>
</tr>
<tr>
<td>B.</td>
<td>emptyslots</td>
<td>filledslots</td>
<td>filledslots</td>
<td>emptyslots</td>
</tr>
<tr>
<td>C.</td>
<td>filledslots</td>
<td>emptyslots</td>
<td>emptyslots</td>
<td>filledslots</td>
</tr>
</tbody>
</table>
Add Semaphores for Synchronization

shared int buf[N], in = 0, out = 0;
shared sem filledslots = 0, emptyslots = N;

Producer
while (TRUE) {
    wait (emptyslots);
    buf[in] = Produce ();
    in = (in + 1)%N;
    signal (filledslots);
}

Consumer
while (TRUE) {
    wait (filledslots);
    Consume (buf[out]);
    out = (out + 1)%N;
    signal (emptyslots);
}

• Buffer empty, Consumer waits
• Buffer full, Producer waits
• Don’t confuse synchronization with mutual exclusion
Synchronization: More than Mutexes

• “I want to block a thread until something specific happens.”
  – Condition variable: wait for a condition to be true
Condition Variables

• In the pthreads library:
  – `pthread_cond_init`: Initialize CV
  – `pthread_cond_wait`: Wait on CV
  – `pthread_cond_signal`: Wakeup one waiter
  – `pthread_cond_broadcast`: Wakeup all waiters

• Condition variable is associated with a mutex:
  1. Lock mutex, realize conditions aren’t ready yet
  2. Temporarily give up mutex until CV signaled
  3. Reacquire mutex and wake up when ready
while (TRUE) {
   //independent code

   lock(m);
   while (conditions bad)
      wait(cond, m);

   //proceed knowing that conditions are now good
   signal (other_cond);  // Let other thread know
   unlock(m);
}

Condition Variable Pattern
**Condition Variable Example**

shared int buf[N], in = 0, out = 0;
shared int count = 0;  // # of items in buffer
shared mutex m;
shared cond notempty, notfull;

**Producer**
while (TRUE) {
    item = Produce();

    lock(m);
    while (count == N)
        wait(m, notfull);

    buf[in] = item;
    in = (in + 1)%N;
    count += 1;

    signal (notempty);
    unlock(m);
}

**Consumer**
while (TRUE) {
    lock(m);
    while (count == 0)
        wait(m, notempty);

    item = buf[out];
    out = (out + 1)%N;
    count -= 1;

    signal (notfull);
    unlock(m);

    Consume(item);
}
Synchronization: More than Mutexes

• “I want to block a thread until something specific happens.”
  – Condition variable: wait for a condition to be true

• “I want all my threads to sync up at the same point.”
  – Barrier: wait for everyone to catch up.
Barriers

• Used to coordinate threads, but also other forms of concurrent execution.

• Often found in simulations that have discrete rounds. (e.g., game of life)
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
    while (...) {
        compute_sim_round()
        barrier_wait(&b)
    }
}

Barrier (0 waiting)
Barrier Example, N Threads

shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
  while (...) {
    compute_sim_round()
    barrier_wait(&b)
  }
}

Threads make progress computing current round at different rates.
Barrier Example, N Threads

```c
shared barrier b;
init_barrier(&b, N);
create_threads(N, func);

void *func(void *arg) {
    while (...) {
        compute_sim_round()
        barrier_wait(&b)
    }
}
```

Threads that make it to barrier must wait for all others to get there.

Time

Barrier (3 waiting)
Barrier Example, N Threads

shared barrier b;
init_barrier(&b, N);
create_threads(N, func);

void *func(void *arg) {
  while (...) {
    compute_sim_round();
    barrier_wait(&b)
  }
}

Barrier allows threads to pass when N threads reach it.
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
  while (...) {
    compute_sim_round()
    barrier_wait(&b)
  }
}

Threads compute next round, wait on barrier again, repeat...

Barrier (0 waiting)

T0  T1  T2  T3  T4
Synchronization: More than Mutexes

• “I want to block a thread until something specific happens.”
  – Condition variable: wait for a condition to be true

• “I want all my threads to sync up at the same point.”
  – Barrier: wait for everyone to catch up.

• “I want my threads to share a critical section when they’re reading, but still safely write.”
  – Readers/writers lock: distinguish how lock is used
Readers/Writers

• Readers/Writers Problem:
  – An object is shared among several threads
  – Some threads only read the object, others only write it
  – We can safely allow multiple readers
  – But only one writer

• pthread_rwlock_t:
  – pthread_rwlock_init: initialize rwlock
  – pthread_rwlock_rdlock: lock for reading
  – pthread_rwlock_wrlock: lock for writing
Common Thread Patterns

• Producer / Consumer (a.k.a. Bounded buffer)

• Thread pool (a.k.a. work queue)

• Thread per client connection
Thread Pool / Work Queue

• Common way of structuring threaded apps:
Thread Pool / Work Queue

• Common way of structuring threaded apps:

Queue of work to be done:  🔄����������

Thread Pool  🟡🟡🟡🟡🟡⬛⬛
Thread Pool / Work Queue

• Common way of structuring threaded apps:
Thread Pool / Work Queue

• Common way of structuring threaded apps:

As threads finish work at their own rate, they grab the next item in queue.

Common for “embarrassingly parallel” algorithms.

Works across the network too!
Thread Per Client

• Consider Web server:
  – Client connects
  – Client asks for a page:
    • http://web.cs.swarthmore.edu/~kwebb/cs31
    • “Give me /~kwebb/cs31”
  – Server looks through file system to find path (I/O)
  – Server sends back html for client browser (I/O)

• Web server does this for MANY clients at once
Thread Per Client

• Server “main” thread:
  – Wait for new connections
  – Upon receiving one, spawn new client thread
  – Continue waiting for new connections, repeat...

• Client threads:
  – Read client request, find files in file system
  – Send files back to client
  – **Nice property:** Each client is independent
  – **Nice property:** When a thread does I/O, it gets blocked for a while. OS can schedule another one.
Summary

• Many ways to solve the same classic problems
  – Producer/Consumer: semaphores, CVs, messages

• There’s more to synchronization than just mutual exclusion!
  – CVs, barriers, RWlocks, and others.