CS31: Introduction to Computer Systems

Week 14, Class 1
Other Synchronization Problems
04/30/24

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Agenda

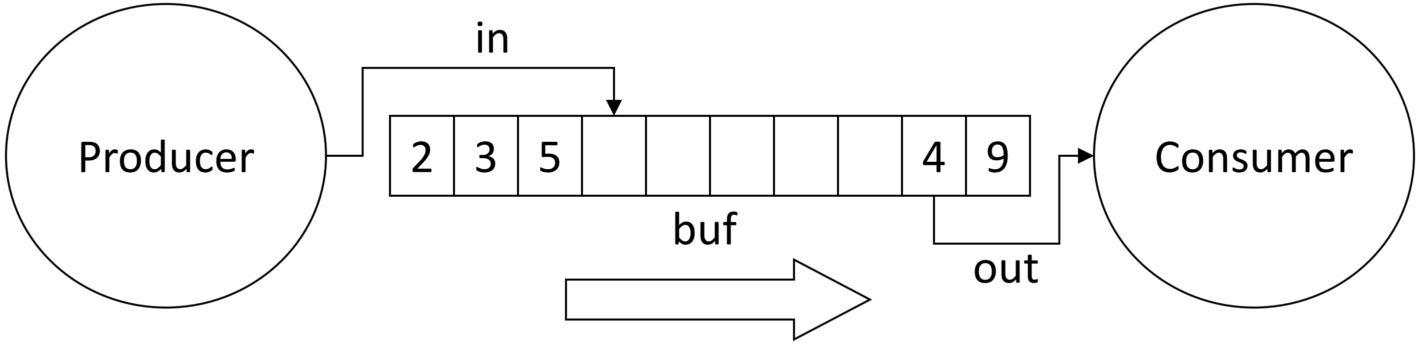
- Classic thread patterns

- Pthreads primitives and examples of other forms of synchronization:
  - Barriers
  - Condition variables
  - 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;
```

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

- 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?

```
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);
}
```

Answer choice	X	Y	Z	W
A.	emptyslots	emptyslots	filledslots	filledslots
B.	emptyslots	filledslots	filledslots	emptyslots
C.	filledslots	emptyslots	emptyslots	filledslots

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
- <u>Don’t confuse synchronization with mutual exclusion</u>

Synchronization: More than Mutexes

- "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)

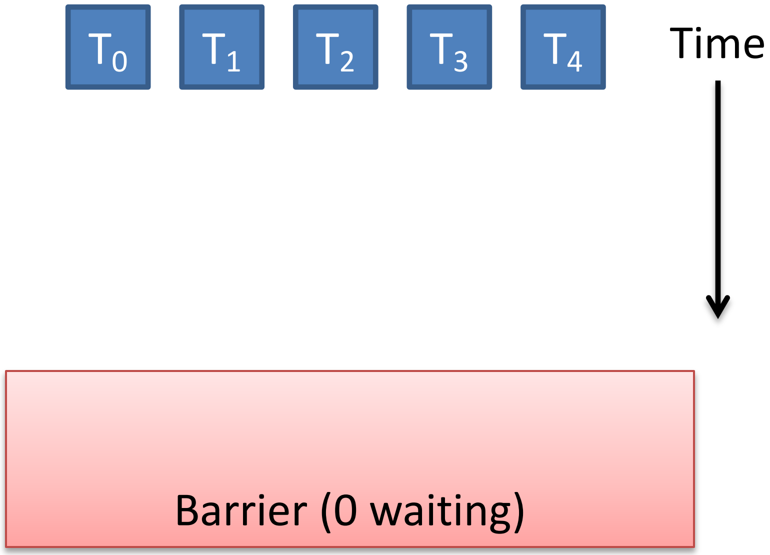
Barrier Example, N Threads

```
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

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



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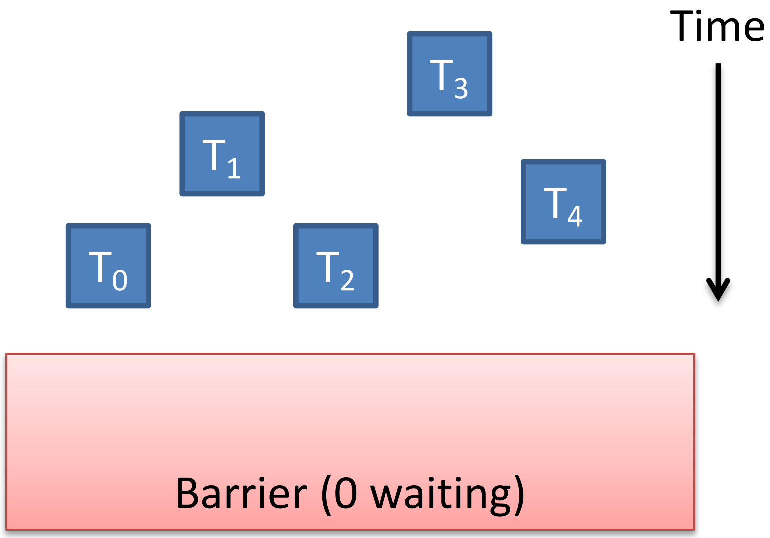
  }
}
```

Threads make progress computing current round at different rates.



Barrier Example, N Threads

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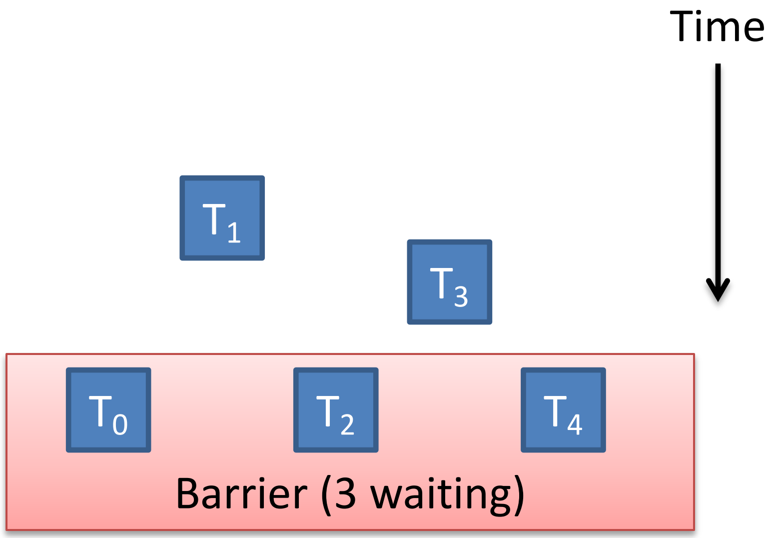
    barrier_wait(&b)
  }
}
```

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



Barrier Example, N Threads

```
shared barrier b;

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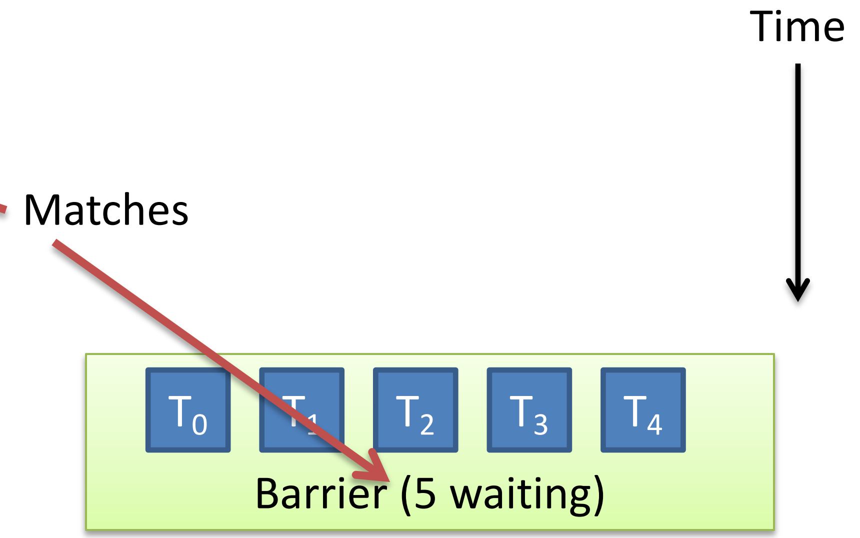
    barrier_wait(&b)
  }
}
```

Barrier allows threads to pass when N threads reach it.



Barrier Example, N Threads

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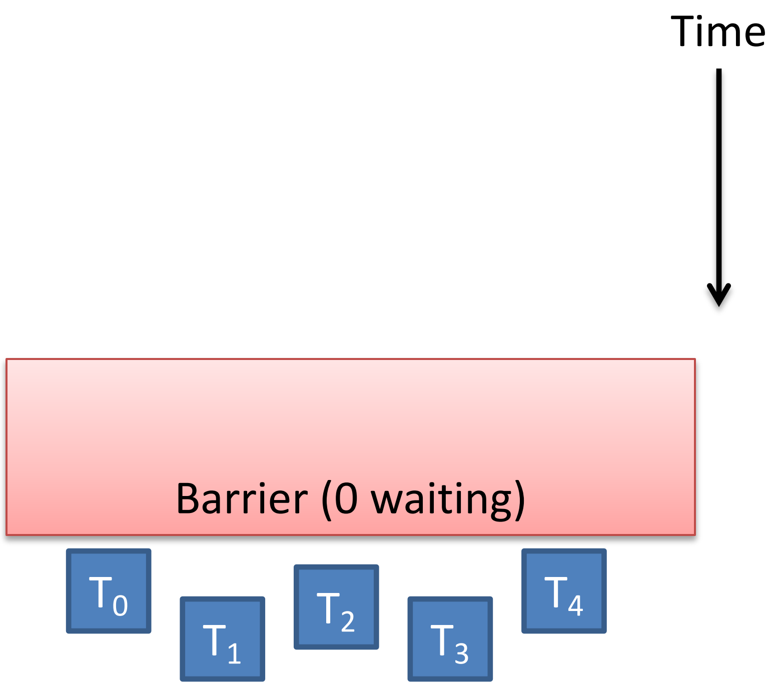
shared barrier b;

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…



Synchronization: More than Mutexes

- "I want all my threads to sync up at the same point."
  - Barrier: wait for everyone to catch up.

- "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

Condition Variable Pattern

```
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 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 all my threads to sync up at the same point.”
  - Barrier: wait for everyone to catch up.

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

- “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

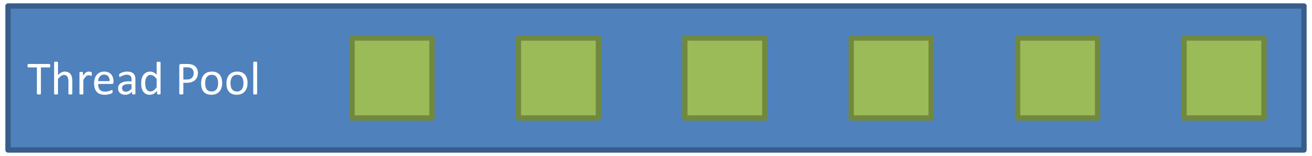
- Readers/Writers Problem:
  - An object is shared among several threads
  - Some threads only read the object, others only write it
  - We can safely allow multiple readers
  - But only one writer
- pthread_rwlock_t:
  - pthread_rwlock_init: initialize rwlock
  - pthread_rwlock_rdlock: lock for reading
  - 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

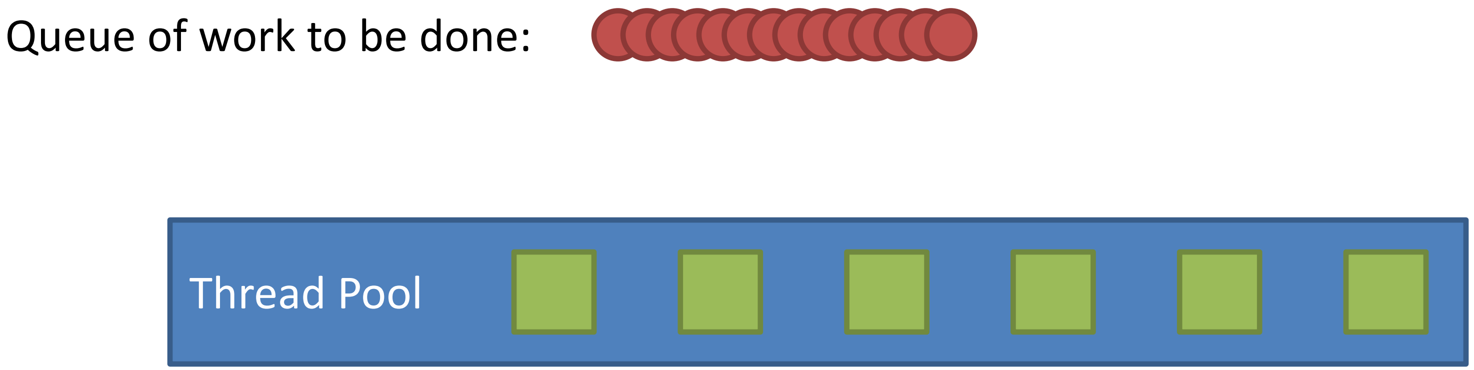
Thread Pool / Work Queue

- Common way of structuring threaded apps:



Thread Pool / Work Queue

- Common way of structuring threaded apps:



Thread Pool / Work Queue

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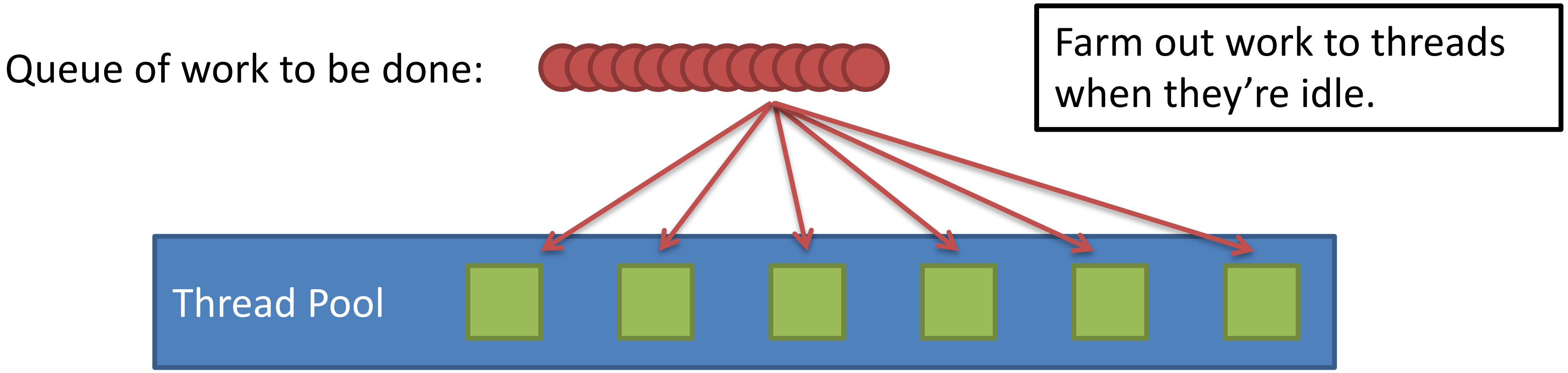
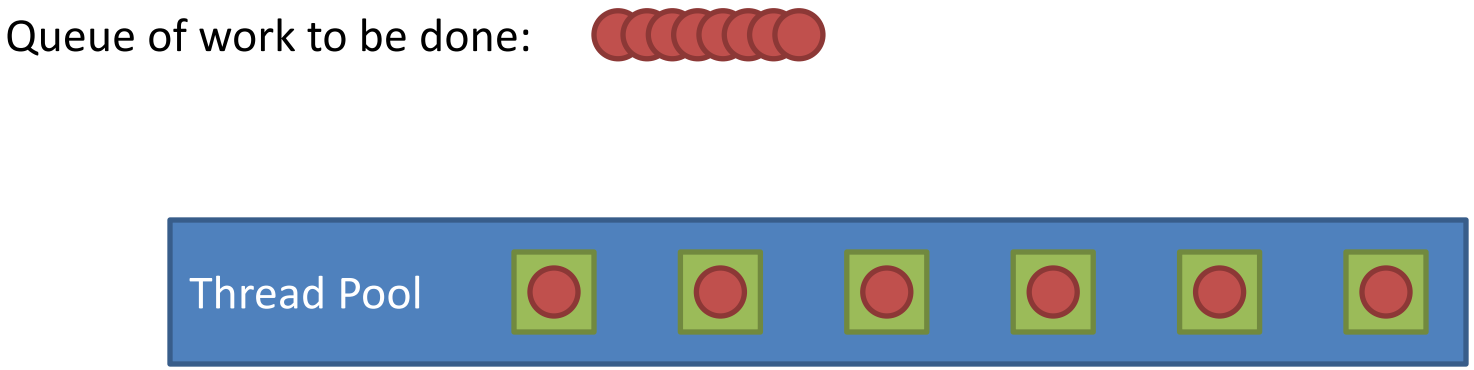


Thread Pool / Work Queue

- 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
  - <u>Nice property:</u> Each client is independent
  - <u>Nice property:</u> 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.