CONCURRENCY: QUEUE LOCKS, CONDITION VARIABLES

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CS 537, Spring 2019

ADMINISTRIVIA

- Project 3 is out
- Project 2a grades are out

AGENDA / LEARNING OUTCOMES

Concurrency

- How do we make locks more efficient?
- How to support threads that need to conditionally execute?

RECAP

LOCK IMPLEMENTATION GOALS

Correctness

- *Mutual exclusion*
  Only one thread in critical section at a time
- *Progress* (deadlock-free)
  If several simultaneous requests, must allow one to proceed
- *Bounded* (starvation-free)
  Must eventually allow each waiting thread to enter

Fairness: Each thread waits for same amount of time

Performance: CPU is not used unnecessarily

LOCK IMPLEMENTATION WITH XCHG

```
typedef struct __lock_t {
    int flag;
} lock_t;

void init(lock_t *lock) {
    lock->flag = ??;
}

void acquire(lock_t *lock) {
    while(xchg(&lock->flag, 1) == 1) ;
    // spin-wait (do nothing)
}

void release(lock_t *lock) {
    lock->flag = 0;
}
```

FAIRNESS: TICKET LOCKS

Idea: reserve each thread's turn to use a lock.

Each thread spins until their turn.

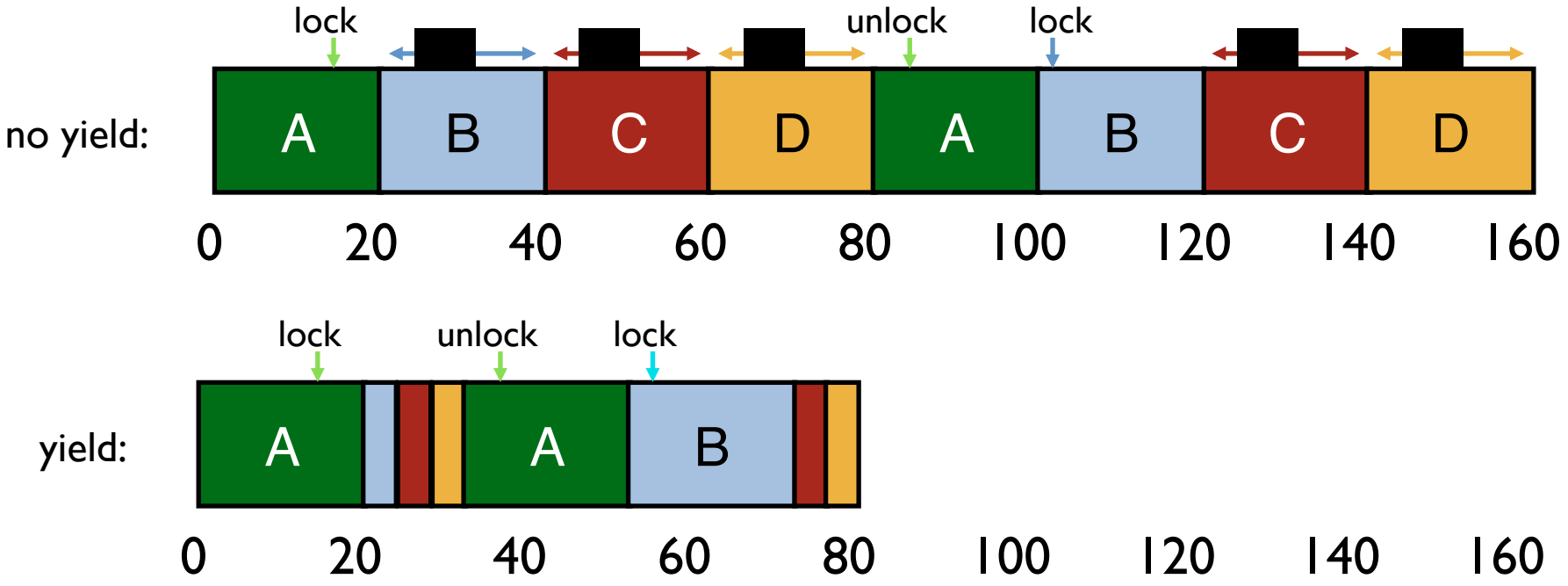
Use new atomic primitive, fetch-and-add

```
int FetchAndAdd(int *ptr) {
   int old = *ptr;
   *ptr = old + 1;
   return old;
}
```

Acquire: Grab ticket; Spin while not thread's ticket != turn

Release: Advance to next turn

YIELD INSTEAD OF SPIN



https://tinyurl.com/cs537-sp19-bunny5

Assuming round robin scheduling, 10ms time slice
Processes A, B, C, D, E, F, G, H, I, J in the system

Timeline
A: lock() … compute … unlock()
B: lock() … compute … unlock()
C: lock()

YIELD VS SPIN

Assuming round robin scheduling, 10ms time slice
Processes A, B, C, D, E, F, G, H, I, J in the system

Timeline
A: lock() … compute … unlock()
B: lock() … compute … unlock()
C: lock()

If A's compute is 20ms long, starting at t = 0, when does B get lock with spin ?

If B's compute is 30ms long, when does C get lock with spin ?

If context switch time = 1ms, when does B get lock with yield ?

SPINLOCK PERFORMANCE

Waste of CPU cycles?

- Without yield: O(threads * **time_slice**)
- With yield: O(threads * **context_switch**)

Even with yield, spinning is slow with high thread contention

Next improvement: Block and put thread on waiting queue instead of spinning

QUEUE LOCKS

LOCK IMPLEMENTATION: BLOCK WHEN WAITING

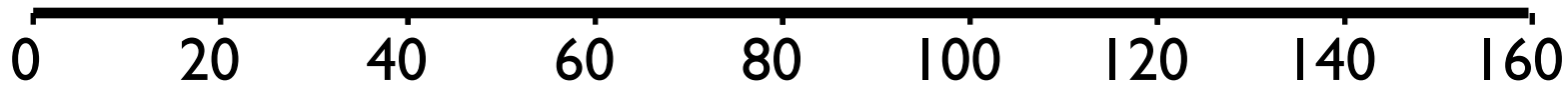
Remove waiting threads from scheduler ready queue
(e.g., park() and unpark(threadID))

Scheduler runs any thread that is **ready**

RUNNABLE: A, B, C, D

RUNNING:

WAITING:



LOCK IMPLEMENTATION: BLOCK WHEN WAITING

```
typedef struct {
   bool lock = false;
   bool guard = false;
   queue_t q;
} LockT;
```

```
void acquire(LockT *l) {
   while (XCHG(&l->guard, true));
   if (l->lock) {
         qadd(l->q, tid);
         l->guard = false;
         park();     // blocked
   } else {
         l->lock = true;
         l->guard = false;
   }
}

void release(LockT *l) {
   while (XCHG(&l->guard, true));
   if (qempty(l->q)) l->lock=false;
   else unpark(qremove(l->q));
   l->guard = false;
}
```

LOCK IMPLEMENTATION: BLOCK WHEN WAITING

(a) Why is **guard** used?

(b) Why okay to **spin** on guard?

(c) In release(), why not set lock=false when unpark?

(d) Is there a race condition?

```
void acquire(LockT *l) {
   while (XCHG(&l->guard, true));
   if (l->lock) {
         qadd(l->q, tid);
         l->guard = false;
         park();      // blocked
   } else {
         l->lock = true;
         l->guard = false;
   }
}

void release(LockT *l) {
   while (XCHG(&l->guard, true));
   if (qempty(l->q)) l->lock=false;
   else unpark(qremove(l->q));
   l->guard = false;
}
```

RACE CONDITION

Thread 1 (in lock)

```
if (l->lock) {
    qadd(l->q, tid);
    l->guard = false;



    park();    // block
```

Thread 2 (in unlock)

```
while (TAS(&l->guard, true));
if (qempty(l->q)) // false!!
else unpark(qremove(l->q));
l->guard = false;
```

BLOCK WHEN WAITING: FINAL CORRECT LOCK

```
typedef struct {
   bool lock = false;
   bool guard = false;
   queue_t q;
} LockT;
```

setpark() fixes race condition

```
void acquire(LockT *l) {
   while (TAS(&l->guard, true));
   if (l->lock) {
         qadd(l->q, tid);
         setpark(); // notify of plan
         l->guard = false;
         park(); // unless unpark()
   } else {
         l->lock = true;
         l->guard = false;
   }
}
void release(LockT *l) {
   while (TAS(&l->guard, true));
   if (qempty(l->q)) l->lock=false;
   else unpark(qremove(l->q));
   l->guard = false;
}
```

https://tinyurl.com/cs537-sp19-bunny6

YIELD VS BLOCKING

Assuming round robin scheduling, 10ms time slice
Processes A, B, C, D, E, F, G, H, I, J in the system

Timeline
A: lock() … compute … unlock()
B: lock() … compute … unlock()
C: lock() …
…

If A's compute is 30ms long, starting at t = 0, when does B get lock with yield ?

If A's compute is 30ms long, starting at t = 0, when does B get lock with blocking ?

SPIN-WAITING VS BLOCKING

Each approach is better under different circumstances

Uniprocessor

- Waiting process is scheduled → Process holding lock isn't
- Waiting process should always relinquish processor
- Associate queue of waiters with each lock (as in previous implementation)

Multiprocessor

- Waiting process is scheduled → Process holding lock might be
- Spin or block depends on how long, t, before lock is released
  - Lock released quickly → Spin-wait
  - Lock released slowly → Block
  - Quick and slow are relative to context-switch cost, C

CONDITION VARIABLES

CONCURRENCY OBJECTIVES

Mutual exclusion (e.g., A and B don't run at same time)

- solved with *locks*

Ordering (e.g., B runs after A does something)

- solved with *condition variables* and *semaphores*

ORDERING EXAMPLE: JOIN

```
pthread_t p1, p2;
Pthread_create(&p1, NULL, mythread, "A");
Pthread_create(&p2, NULL, mythread, "B");
// join waits for the threads to finish
Pthread_join(p1, NULL);
Pthread_join(p2, NULL);
printf("main: done\n [balance: %d]\n [should: %d]\n",
    balance, max*2);
return 0;
```

how to implement join()?

CONDITION VARIABLES

Condition Variable: queue of waiting threads

B waits for a signal on CV before running

- wait(CV, …)

A sends signal to CV when time for ***B*** to run

- signal(CV, …)

CONDITION VARIABLES

wait(cond_t *cv, mutex_t *lock)

- assumes the lock is held when wait() is called
- puts caller to sleep + releases the lock (atomically)
- when awoken, reacquires lock before returning

signal(cond_t *cv)

- wake a single waiting thread (if >= 1 thread is waiting)
- if there is no waiting thread, just return, doing nothing

JOIN IMPLEMENTATION: ATTEMPT 1

Parent:

```
void thread_join() {
        Mutex_lock(&m);       // x
        Cond_wait(&c, &m);    // y
        Mutex_unlock(&m);     // z
}
```

Child:

```
void thread_exit() {
        Mutex_lock(&m);       // a
        Cond_signal(&c);      // b
        Mutex_unlock(&m);     // c
}
```

Example schedule:

Parent:	x	y				z
Child:			a	b	c	

JOIN IMPLEMENTATION: ATTEMPT 1

Parent:

```
void thread_join() {
        Mutex_lock(&m);       // x
        Cond_wait(&c, &m);    // y
        Mutex_unlock(&m);     // z
}
```

Child:

```
void thread_exit() {
        Mutex_lock(&m);       // a
        Cond_signal(&c);      // b
        Mutex_unlock(&m);     // c
}
```

Example broken schedule:

Parent:				x	y
Child:	a	b	c		

RULE OF THUMB 1

Keep state in addition to CV's!

CV's are used to signal threads when state changes

If state is already as needed, thread doesn't wait for a signal!

JOIN IMPLEMENTATION: ATTEMPT 2

Parent:

```
void thread_join() {
        Mutex_lock(&m);          // w
        if (done == 0)           // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);        // z
}
```

Child:

```
void thread_exit() {
        done = 1;          // a
        Cond_signal(&c); // b
}
```

Parent: w x y z

Child: a b

JOIN IMPLEMENTATION: ATTEMPT 2

Parent:

```
void thread_join() {
        Mutex_lock(&m);          // w
        if (done == 0)           // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);        // z
}
```

Child:

```
void thread_exit() {
        done = 1;          // a
        Cond_signal(&c); // b
}
```

Parent: w x y

Child: a b

JOIN IMPLEMENTATION: CORRECT

Parent:

```
void thread_join() {
        Mutex_lock(&m);          // w
        if (done == 0)           // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);        // z
}
```

Child:

```
void thread_exit() {
        Mutex_lock(&m);      // a
        done = 1;            // b
        Cond_signal(&c);     // c
        Mutex_unlock(&m);    // d
}
```

Parent: w x y z

Child: a b c

Use mutex to ensure no race between interacting with state and wait/signal

PRODUCER/CONSUMER PROBLEM

EXAMPLE: UNIX PIPES

A pipe may have many writers and readers

Internally, there is a finite-sized buffer

Writers add data to the buffer

- Writers have to wait if buffer is full

Readers remove data from the buffer

- Readers have to wait if buffer is empty

EXAMPLE: UNIX PIPES

start

Buf: 

end

EXAMPLE: UNIX PIPES

Implementation:

- reads/writes to buffer require locking
- when buffers are full, writers must wait
- when buffers are empty, readers must wait

PRODUCER/CONSUMER PROBLEM

Producers generate data (like pipe writers)

Consumers grab data and process it (like pipe readers)

Producer/consumer problems are frequent in systems (e.g. web servers)

General strategy use condition variables to:

- make producers wait when buffers are full
- make consumers wait when there is nothing to consume

PRODUCE/CONSUMER EXAMPLE

Start with easy case:

- 1 producer thread
- 1 consumer thread
- 1 shared buffer to fill/consume (max = 1)

Numfull = number of buffers currently filled

numfull

Thread 1 state:

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m);
        if(numfull == max)
            Cond_wait(&cond, &m);
        do_fill(i);
        Cond_signal(&cond);
        Mutex_unlock(&m);
    }
}
```

Thread 2 state:

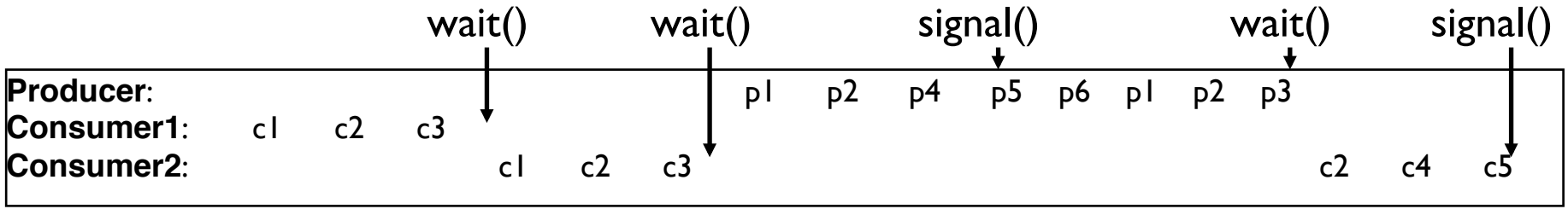
```
void *consumer(void *arg) {
    while(1) {
        Mutex_lock(&m);
        if(numfull == 0)
            Cond_wait(&cond, &m);
        int tmp = do_get();
        Cond_signal(&cond);
        Mutex_unlock(&m);
        printf("%d\n", tmp);
    }
}
```

WHAT ABOUT 2 CONSUMERS?

Can you find a problematic timeline with 2 consumers (still 1 producer)?

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m); // p1
        if(numfull == max) //p2
            Cond_wait(&cond, &m); //p3
        do_fill(i); // p4
        Cond_signal(&cond); //p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while(1) {
        Mutex_lock(&m);  // c1
        if(numfull == 0) // c2
            Cond_wait(&cond, &m); // c3
        int tmp = do_get(); // c4
        Cond_signal(&cond); // c5
        Mutex_unlock(&m); // c6
        printf("%d\n", tmp); // c7
    }
}
```



HOW TO WAKE THE RIGHT THREAD?

Wake all the threads!?

Better solution (usually): use two condition variables

PRODUCER/CONSUMER: TWO CVS

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        if (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i);  // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        if (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

PRODUCER/CONSUMER: TWO CVS

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        if (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i);  // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        if (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

1. consumer1 waits because numfull == 0
2. producer increments numfull, wakes consumer1
3. before consumer1 runs, consumer2 runs, grabs entry, sets numfull=0.
4. consumer2 then reads bad data.

PRODUCER/CONSUMER: TWO CVS AND WHILE

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        while (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i);  // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        while (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

No concurrent access to shared state

Every time lock is acquired, assumptions are reevaluated

A consumer will get to run after every do_fill()

A producer will get to run after every do_get()

GOOD RULE OF THUMB 3

Whenever a lock is acquired, recheck assumptions about state!

Another thread could grab lock in between signal and wakeup from wait

Note that some libraries also have "spurious wakeups" (may wake multiple waiting threads at signal or at any time)

SUMMARY: RULES OF THUMB FOR CVS

1. Keep state in addition to CV's
2. Always do wait/signal with lock held
3. Whenever thread wakes from waiting, recheck state

NEXT STEPS

Project 3: Out now!

Next class: Semaphores

WAKING ALL WAITING THREADS

wait(cond_t *cv, mutex_t *lock)
- assumes the lock is held when wait() is called
- puts caller to sleep + releases the lock (atomically)
- when awoken, reacquires lock before returning

signal(cond_t *cv)
- wake a single waiting thread (if >= 1 thread is waiting)
- if there is no waiting thread, just return, doing nothing

broadcast(cond_t *cv)
- wake **all** waiting threads (if >= 1 thread is waiting)
- if there are no waiting thread, just return, doing nothing

WHEN TO SPIN-WAIT? WHEN TO BLOCK?

If know how long**, t,** before lock released, can determine optimal behavior

How much CPU time is wasted when spin-waiting?

How much wasted when block?

What is the best action when t<C?

When t>C?