Synchronization II

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CS 3410, Spring 2015
Computer Science
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P&H Chapter 2.11

Announcements

Project3 *due tomorrow*, Friday, April 24th

- **Games night Monday, May 4th, 5-7pm. Location: B17 Upson**
- **Come, eat, drink, have fun and be merry!**

Prelim2 is *next week*, Thursday, April 30th

- Time and Location: 7:30pm in Statler Auditorium
- Old prelims are online in CMS
- Prelim Review Session:

    Sunday, April 26, 7-9pm in B14 Hollister Hall

    Tuesday, April 28, 7-8pm in B14 Hollister Hall

Project4: Final project out next week

- Demos: May 12 and 13
- ***Will NOT be able to use slip days***

Announcements

Next three weeks

- Week 12 (Apr 21): Lab4 due in-class, Proj3 due Fri, HW2 due Sat
- Week 13 (Apr 28): Proj4 release, Prelim2
- Week 14 (May 5): Proj3 tournament Mon, Proj4 design doc due

Final Project for class

- Week 15 (May 12): Proj4 due Wed, May 13th

Cache Coherency and Synchronization Problem

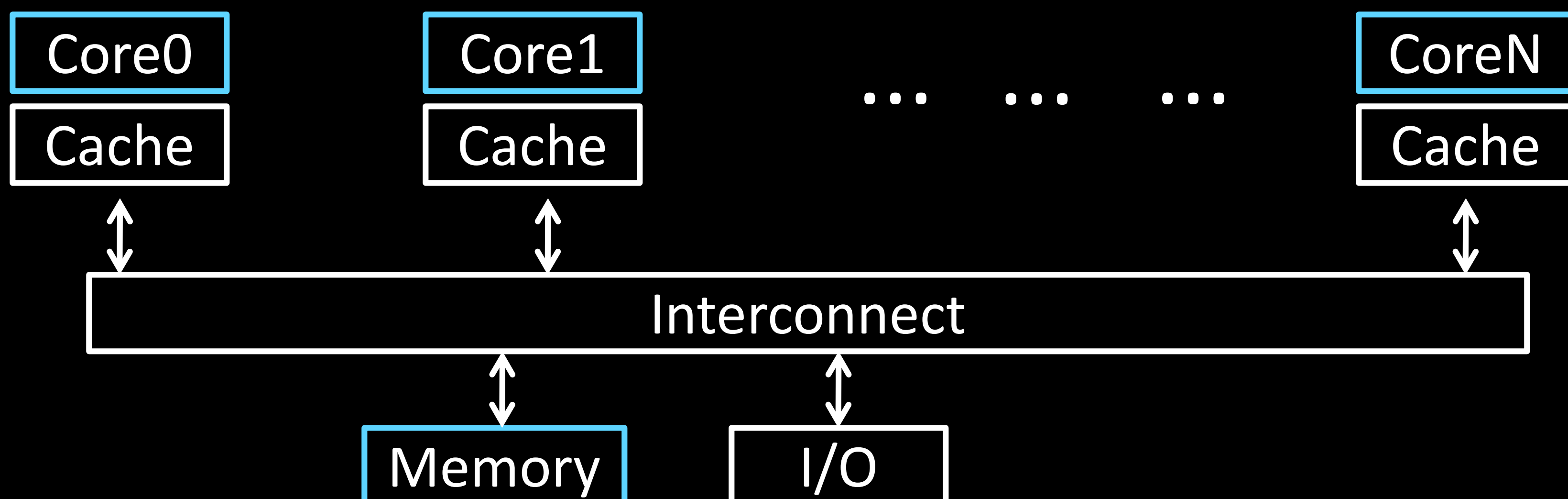
Thread A (on Core0)

```
for(int i = 0, i < 5; i++) {
        x = x + 1
}
```

Thread B (on Core1)

```
for(int j = 0; j < 5; j++) {
        x = x + 1
}
```

x should be greater than 1 after both threads loop at least once!



Cache Coherency and Synchronization Problem

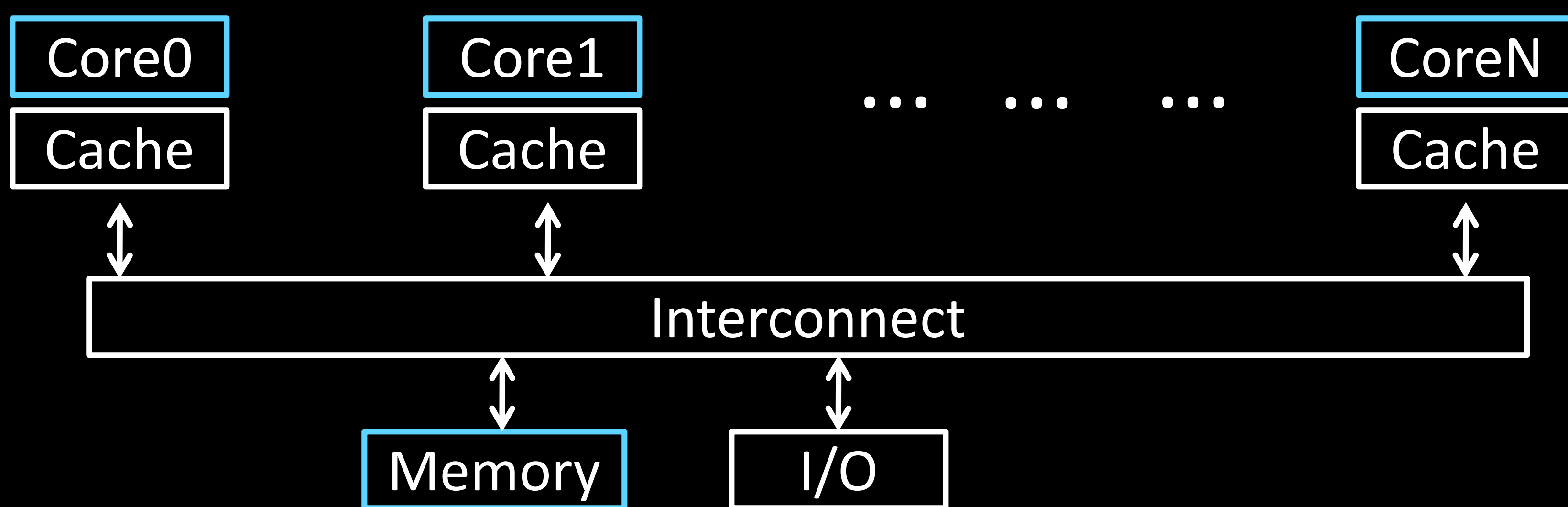
Thread A (on Core0)

```
for(int i = 0, i < 5; i++) {
$t0=0   LW $t0, addr(x)
$t0=1   ADDIU $t0, $t0, 1
  x=1   SW $t0, addr(x)
}
```

Thread B (on Core1)

```
for(int j = 0; j < 5; j++) {
$t0=0   LW $t0, addr(x)
$t0=1   ADDIU $t0, $t0, 1
  x=1   SW $t0, addr(x)
}
```

x should be greater than 1 after both threads loop at least once!



Programming with Threads

Need it to exploit multiple processing units

…to provide interactive applications

…to parallelize for multicore

…to write servers that handle many clients

Problem: hard even for experienced programmers

- Behavior can depend on subtle timing differences
- Bugs may be impossible to reproduce

Needed: synchronization of threads

Goals for Today

Synchronization

- Threads and processes
- Critical sections, race conditions, and mutexes
- Atomic Instructions
  - HW support for synchronization
  - Using sync primitives to build concurrency-safe data structures
- Language level synchronization

Programming with Threads

Concurrency poses challenges for:

Correctness

- Threads accessing shared memory should not interfere with each other

Liveness

- Threads should not get stuck, should make forward progress

Efficiency

- Program should make good use of available computing resources (e.g., processors).

Fairness

- Resources apportioned fairly between threads

HW support for critical sections

How to implement mutex locks?

What are the hardware primitives?

Then, use these mutex locks to implement critical sections, and use critical sections to write parallel safe programs.

Mutexes

Q: How to implement critical section in code?

A: Lots of approaches....

Mutual Exclusion Lock (mutex)

lock(m): wait till it becomes free, then lock it

unlock(m): unlock it

```
safe_increment() {
    pthread_mutex_lock(&m);
    hits = hits + 1;
    pthread_mutex_unlock(&m)
}
```

Synchronization in MIPS

Load linked: `LL rt, offset(rs)`

Store conditional: `SC rt, offset(rs)`

- Succeeds if location not changed since the `LL`
  - Returns 1 in rt
- Fails if location is changed
  - Returns 0 in rt

Any time a processor intervenes and modifies the value in memory between the LL and SC instruction, the SC returns 0 in $t0, causing the code to try again.

i.e. use this value 0 in $t0 to try again.

Synchronization in MIPS

Load linked: `LL rt, offset(rs)`

Store conditional: `SC rt, offset(rs)`

- Succeeds if location not changed since the LL
  - Returns 1 in rt
- Fails if location is changed
  - Returns 0 in rt

Example: atomic incrementor

i++

↓

```
LW $t0, 0($s0)
ADDIU $t0, $t0, 1
SW $t0, 0($s0)
```

→

atomic(i++)

↓

```
try: LL $t0, 0($s0)
     ADDIU $t0, $t0, 1
     SC $t0, 0($s0)
     BEQZ $t0, try
```

Synchronization in MIPS

Load linked: `LL rt, offset(rs)`

Store conditional: `SC rt, offset(rs)`

- Succeeds if location not changed since the LL
  - Returns 1 in rt
- Fails if location is changed
  - Returns 0 in rt

Example: atomic incrementor

Time Step	Thread A	Thread B	Thread A \$t0	Thread B \$t0	Memory M[\$s0]
0					0
1	try: LL \$t0, 0(\$s0)	try: LL \$t0, 0(\$s0)			
2	ADDIU \$t0, \$t0, 1	ADDIU \$t0, \$t0, 1			
3	SC \$t0, 0(\$s0)	SC \$t0, 0 (\$s0)			
4	BEQZ \$t0, try	BEQZ \$t0, try			

Synchronization in MIPS

Load linked: `LL rt, offset(rs)`

Store conditional: `SC rt, offset(rs)`

- Succeeds if location not changed since the `LL`
  - Returns 1 in rt
- Fails if location is changed
  - Returns 0 in rt

Example: atomic incrementor

Time Step	Thread A	Thread B	Thread A \$t0	Thread B \$t0	Memory M[\$s0]
0					0
1	try: LL \$t0, 0(\$s0)	try: LL \$t0, 0(\$s0)	0	0	0
2	ADDIU \$t0, \$t0, 1	ADDIU \$t0, \$t0, 1	1	1	0
3	SC \$t0, 0(\$s0)	SC \$t0, 0 (\$s0)	0	1	1
4	BEQZ \$t0, try	BEQZ \$t0, try	0	1	1

Failure – try again

Success!

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
   while(test_and_set(m)){}
}
```

```
int test_and_set(int *m) {
     old = *m;   LL    Atomic
     *m = 1;     SC
     return old;
}
```

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
   while(test_and_set(m)){}
}
```

```
int test_and_set(int *m) {
try:    LI $t0, 1
        LL $t1, 0($a0)
        SC $t0, 0($a0)
        MOVE $v0, $t1
}
```

BEQZ $t0, try

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
   while(test_and_set(m)){}
}

int test_and_set(int *m) {
 try:
      LI $t0, 1
      LL $t1, 0($a0)
      SC $t0, 0($a0)
      BEQZ $t0, try
      MOVE $v0, $t1
}
```

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
   test_and_set:
           LI $t0, 1
           LL $t1, 0($a0)
           BNEZ $t1, test_and_set
           SC $t0, 0($a0)
           BEQZ $t0, test_and_set
}

mutex_unlock(int *m) {
     *m = 0;
}
```

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
   test_and_set:
           LI $t0, 1
           LL $t1, 0($a0)
           BNEZ $t1, test_and_set
           SC $t0, 0($a0)
           BEQZ $t0, test_and_set
}

mutex_unlock(int *m) {
      SW $zero, 0($a0)
}
```

This is called a
Spin lock
Aka spin waiting

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
```

Time Step	Thread A	Thread B	Thread A $t0	Thread A $t1	Thread B $t0	Thread B $t1	Mem M[$a0]
0							0
1	try: LI $t0, 1	try: LI $t0, 1					
2	LL $t1, 0($a0)	LL $t1, 0($a0)					
3	BNEZ $t1, try	BNEZ $t1, try					
4	SC $t0, 0($a0)	SC $t0, 0 ($a0)					
5	BEQZ $t0, try	BEQZ $t0, try					
6							

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
```

Time Step	Thread A	Thread B	Thread A $t0	Thread A $t1	Thread B $t0	Thread B $t1	Mem M[$a0]
0							0
1	try: LI $t0, 1	try: LI $t0, 1	1		1		0
2	LL $t1, 0($a0)	LL $t1, 0($a0)	1	0	1	0	0
3	BNEZ $t1, try	BNEZ $t1, try	1	0	1	0	0
4	SC $t0, 0($a0)	SC $t0, 0 ($a0)	0	0	1	0	1
5	BEQZ $t0, try	BEQZ $t0, try	0	0	1	0	1
6							

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
```

Time Step	Thread A	Thread B	Thread A $t0	Thread A $t1	Thread B $t0	Thread B $t1	Mem M[$a0]
0							0
1	try: LI $t0, 1	try: LI $t0, 1	1		1		0
2	LL $t1, 0($a0)	LL $t1, 0($a0)	1	0	1	0	0
3	BNEZ $t1, try	BNEZ $t1, try	1	0	1	0	0
4	SC $t0, 0($a0)	SC $t0, 0 ($a0)	0	0	1	0	1
5	BEQZ $t0, try	BEQZ $t0, try	0	0	1	0	1
6	try: LI $t0, 1	Critical section					

Failed to get mutex lock – try again

Success grabbing mutex lock!
Inside Critical section

Mutex from LL and SC

Linked load / Store Conditional

m = 0; // m=0 means lock is free; otherwise, if m=1, then lock locked

```
mutex_lock(int *m) {
   test_and_set:
           LI $t0, 1
           LL $t1, 0($a0)
           BNEZ $t1, test_and_set
           SC $t0, 0($a0)
           BEQZ $t0, test_and_set
}

mutex_unlock(int *m) {
      SW $zero, 0($a0)
}
```

This is called a
Spin lock
Aka spin waiting

Mutex from LL and SC

Linked load / Store Conditional

m = 0;

```
mutex_lock(int *m) {
```

Time Step	Thread A	Thread B	Thread A $t0	Thread A $t1	Thread B $t0	Thread B $t1	Mem M[$a0]
0							1
1	try: LI $t0, 1	try: LI $t0, 1					
2							
3							
4							
5							
6							
7							
8							
9							

Mutex from LL and SC

Linked load / Store Conditional

m = 0;

```
mutex_lock(int *m) {
```

Time Step	Thread A	Thread B	Thread A $t0	Thread A $t1	Thread B $t0	Thread B $t1	Mem M[$a0]
0							1
1	try: LI $t0, 1	try: LI $t0, 1	1		1		1
2	LL $t1, 0($a0)	LL $t1, 0($a0)	1	1	1	1	1
3	BNEZ $t1, try	BNEZ $t1, try	1	1	1	1	1
4	try: LI $t0, 1	try: LI $t0, 1	1	1	1	1	1
5	LL $t1, 0($a0)	LL $t1, 0($a0)	1	1	1	1	1
6	BNEZ $t1, try	BNEZ $t1, try	1	1	1	1	1
7	try: LI $t0, 1	try: LI $t0, 1	1	1	1	1	1
8	LL $t1, 0($a0)	LL $t1, 0($a0)	1	1	1	1	1
9	BNEZ $t1, try	BNEZ $t1, try	1	1	1	1	1

Now we can write parallel and correct programs

Thread A

```
for(int i = 0, i < 5; i++) {

      mutex_lock(m);

            x = x + 1;

      mutex_unlock(m);

}
```

Thread B

```
for(int j = 0; j < 5; j++) {

      mutex_lock(m);

            x = x + 1;

      mutex_unlock(m);

}
```

Alternative Atomic Instructions

Other atomic hardware primitives

- test and set (x86)
- atomic increment (x86)
- bus lock prefix (x86)
- compare and exchange (x86, ARM deprecated)
- linked load / store conditional

(MIPS, ARM, PowerPC, DEC Alpha, ...)

Synchronization

Synchronization techniques

clever code

- must work despite adversarial scheduler/interrupts
- used by: hackers
- also: noobs

disable interrupts

- used by: exception handler, scheduler, device drivers, …

disable preemption

- dangerous for user code, but okay for some kernel code

mutual exclusion locks (mutex)

- general purpose, except for some interrupt-related cases

Summary

Need parallel abstractions, especially for multicore

Writing correct programs is hard

- Need to prevent data races

Need critical sections to prevent data races

- Mutex, mutual exclusion, implements critical section
- Mutex often implemented using a lock abstraction

Hardware provides synchronization primitives such as **LL** and **SC** (load linked and store conditional) instructions to efficiently implement locks

Next Goal

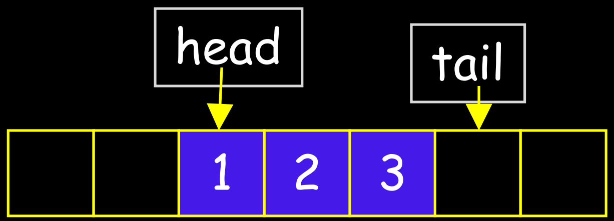
How do we use synchronization primitives to build concurrency-safe data structure?

Attempt#1: Producer/Consumer

Access to shared data must be synchronized

- goal: enforce datastructure invariants

```
// invariant:
// data is in A[h … t-1]
char A[100];
int h = 0, t = 0;
```




```
// producer: add to list tail
void put(char c) {
  A[t] = c;
  t = (t+1)%n;
}
```

Attempt#1: Producer/Consumer

Access to shared data must be synchronized

- goal: enforce datastructure invariants

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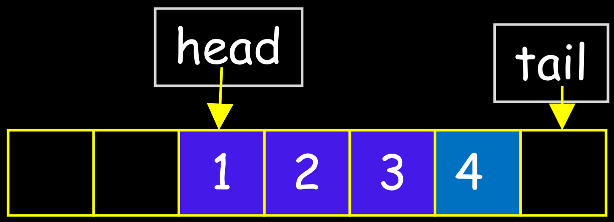


```
// producer: add to list tail
void put(char c) {
  A[t] = c;
  t = (t+1)%n;
}
```

```
// consumer: take from list head
char get() {
  while (h == t) { };
  char c = A[h];
  h = (h+1)%n;
  return c;
}
```

Attempt#1: Producer/Consumer

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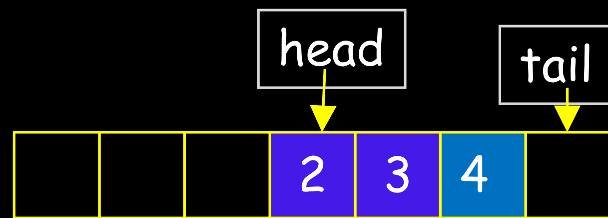


```
// producer: add to list tail
void put(char c) {
  A[t] = c;
  t = (t+1)%n;
}
```

```
// consumer: take from list head
char get() {
  while (h == t) { };
  char c = A[h];
  h = (h+1)%n;
  return c;
}
```

What is wrong with code?

a) Will lose update to ***t*** and/or ***h***
b) Invariant is not upheld
c) Will produce if full
d) Will consume if empty
e) All of the above

Attempt#1: Producer/Consumer

Access to shared data must be synchronized

- goal: enforce datastructure invariants

```
// invariant:
// data is in A[h … t-1]
char A[100];
int h = 0, t = 0;
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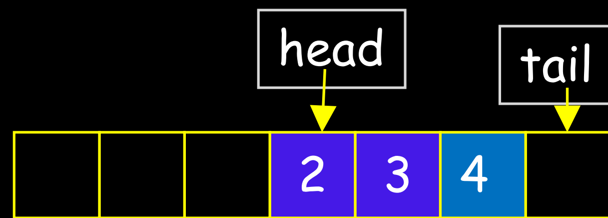



```
// producer: add to list tail
void put(char c) {
  A[t] = c;
  t = (t+1)%n;
}
```

```
// consumer: take from list head
char get() {
  while (h == t) { };
  char c = A[h];
  h = (h+1)%n;
  return c;
}
```

Error: could miss an update to ***t*** or ***h*** due to lack of synchronization

Current implementation will **break invariant:**

only produce if not full and only consume if not empty

Need to synchronize access to shared data

Attempt#2: Protecting an invariant

```
// invariant: (protected by mutex m)
// data is in A[h … t-1]
pthread_mutex_t *m = pthread_mutex_create();
char A[100];
int h = 0, t = 0;
```

```
// producer: add to list tail
void put(char c) {
  pthread_mutex_lock(m);
  A[t] = c;
  t = (t+1)%n;
  pthread_mutex_unlock(m);
}
```

```
// consumer: take from list head
char get() {
  pthread_mutex_lock(m);
  while(h == t) {}
  char c = A[h];
  h = (h+1)%n;
  pthread_mutex_unlock(m);
  return c;
}
```

Rule of thumb: all access and updates that can affect invariant become critical sections

Attempt#2: Protecting an invariant

```
// invariant: (protected by mutex m)
// data is in A[h … t-1]
pthread_mutex_t *m = pthread_mutex_create();
char A[100];
int h = 0, t = 0;
```

BUG: Can't wait while holding lock

```
// producer: add to list tail
void put(char c) {
  pthread_mutex_lock(m);
  A[t] = c;
  t = (t+1)%n;
  pthread_mutex_unlock(m);
}
```

```
// consumer: take from list head
char get() {
  pthread_mutex_lock(m);
  while(h == t) {}
  char c = A[h];
  h = (h+1)%n;
  pthread_mutex_unlock(m);
  return c;
}
```

Rule of thumb: all access and updates that can affect invariant become critical sections

Guidelines for successful mutexing

Insufficient locking can cause races

- Skimping on mutexes? Just say no!

Poorly designed locking can cause deadlock

```
P1: lock(m1);    P2: lock(m2);
    lock(m2);        lock(m1);
```

Circular Wait

- know why you are using mutexes!
- acquire locks in a consistent order to avoid cycles
- use lock/unlock like braces (match them lexically)
  - lock(&m); …; unlock(&m)
  - watch out for return, goto, and function calls!
  - watch out for exception/error conditions!

Attempt#3: Beyond mutexes

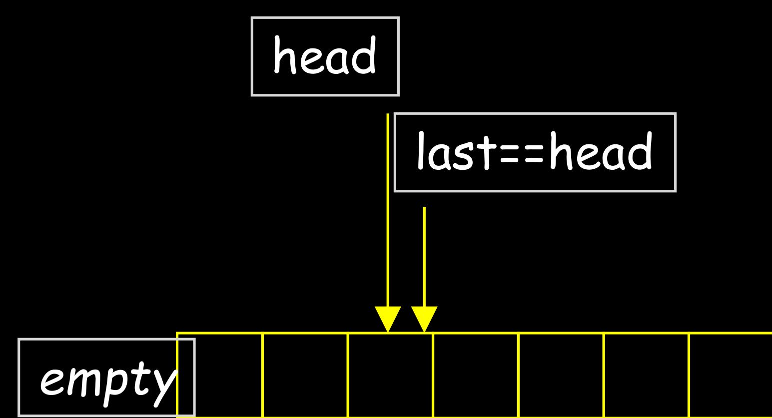
Writers must check for full buffer

& Readers must check for empty buffer

- ideal: don’t busy wait… go to sleep instead

while(empty) {}

```
char get() {
  acquire(L);
  char c = A[h];
  h = (h+1)%n;
  release(L);
  return c;
}
```



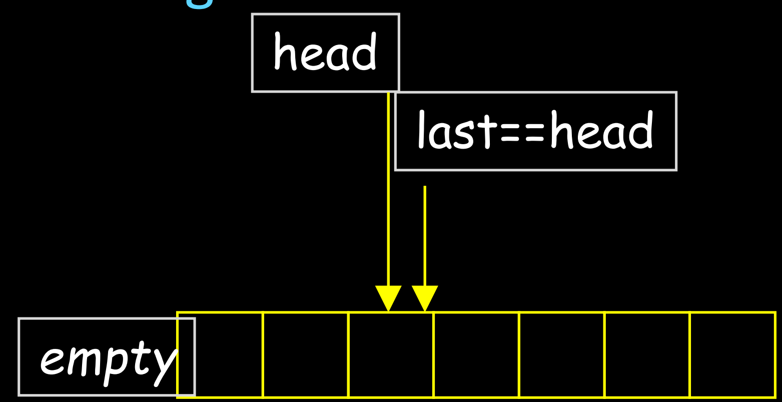
Attempt#3: Beyond mutexes

Writers must check for full buffer
& Readers must check if for empty buffer

- ideal: don’t busy wait… go to sleep instead

```
char get() {
  while (h == t) { };
  acquire(L);
  char c = A[h];
  h = (h+1)%n;
  release(L);
  return c;
}
```

Cannot check condition while
Holding the lock,
BUT, empty condition may no
longer hold in critical section



Dilemma: Have to check while holding lock,

Attempt#3: Beyond mutexes

Writers must check for full buffer

& Readers must check if for empty buffer

- ideal: don't busy wait… go to sleep instead

```
char get() {
  acquire(L);
  while (h == t) { };
  char c = A[h];
  h = (h+1)%n;
  release(L);
  return c;
}
```

Dilemma: Have to check while holding lock,
but cannot wait while hold lock

Attempt#4: Beyond mutexes

Writers must check for full buffer

& Readers must check if for empty buffer

- ideal: don't busy wait… go to sleep instead

```
char get() {
  do {
      acquire(L);
      empty = (h == t);
      if (!empty) {
            c = A[h];
            h = (h+1)%n;
      }
      release(L);
  } while (empty);
  return c;
}
```

Does this work?

a) Yes

b) no

Attempt#4: Beyond mutexes

Writers must check for full buffer

& Readers must check if for empty buffer

- ideal: don’t busy wait… go to sleep instead

```
char get() {
  do {
      acquire(L);
      empty = (h == t);
      if (!empty) {
          c = A[h];
          h = (h+1)%n;
      }
      release(L);
  } while (empty);
  return c;
}
```

It works.

But, it is wasteful

Due to the spinning

Language-level Synchronization

Condition variables

Use [Hoare] a condition variable to wait for a condition to become true (without holding lock!)

wait(m, c) :

- atomically release *m* and sleep, waiting for condition *c*
- wake up holding *m* sometime after *c* was signaled

signal(c) : wake up one thread waiting on *c*

broadcast(c) : wake up all threads waiting on *c*

POSIX (e.g., Linux): pthread_cond_wait, pthread_cond_signal, pthread_cond_broadcast

Attempt#5: Using a condition variable

wait(m, c) : release m, sleep until c, wake up holding m

signal(c) : wake up one thread waiting on c

```
cond_t *not_full = ...;
cond_t *not_empty = ...;
mutex_t *m = ...;

void put(char c) {
  lock(m);
  while ((t-h) % n == 1)
    wait(m, not_full);
  A[t] = c;
  t = (t+1) % n;
  unlock(m);
  signal(not_empty);
}
```

```
char get() {
  lock(m);
  while (t == h)
    wait(m, not_empty);
  char c = A[h];
  h = (h+1) % n;
  unlock(m);
  signal(not_full);
  return c;
}
```

Monitors

A Monitor is a concurrency-safe datastructure, with…

- one mutex
- some condition variables
- some operations

All operations on monitor acquire/release mutex

- one thread in the monitor at a time

Ring buffer was a monitor

Java, C#, etc., have built-in support for monitors

Java concurrency

Java objects can be monitors

- "synchronized" keyword locks/releases the mutex
- Has one (!) builtin condition variable
  - o.wait() = wait(o, o)
  - o.notify() = signal(o)
  - o.notifyAll() = broadcast(o)

- Java wait() can be called even when mutex is not held. Mutex not held when awoken by signal(). Useful?

More synchronization mechanisms

Lots of synchronization variations…
(can implement with mutex and condition vars.)

Reader/writer locks

- Any number of threads can hold a read lock
- Only one thread can hold the writer lock

Semaphores

- N threads can hold lock at the same time

Message-passing, sockets, queues, ring buffers, …

- transfer data and synchronize

Summary

Hardware Primitives: test-and-set, LL/SC, barrier, ...

... used to build ...

Synchronization primitives: mutex, semaphore, ...

... used to build ...

Language Constructs: monitors, signals, ...