Synchronization II

Hakim Weatherspoon
CS 3410, Spring 2012
Computer Science
Cornell University

P&H Chapter 2.11

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
  - Cache coherency causes problems
  - Locks + barriers
- Language level synchronization

Synchronization

Two processors sharing an area of memory

- P1 writes, then P2 reads
- Data race if P1 and P2 don't ***synchronize***
  - Result depends of order of accesses

Hardware support required

- Atomic read/write memory operation
- No other access to the location allowed between the read and write

Could be a single instruction

- E.g., atomic swap of register ↔ memory (e.g. ATS, BTS; x86)
- Or an atomic pair of instructions (e.g. LL and SC; MIPS)

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 swap (to test/set lock variable)

```
try: MOVE $t0,$s4     ;copy exchange value
     LL   $t1,0($s1)  ;load linked
     SC   $t0,0($s1)  ;store conditional
     BEQZ $t0,try     ;branch store fails
     MOVE $s4,$t1     ;put load value in $s4
```

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

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

Two threads, one counter

Example: Web servers use concurrency

Multiple threads handle client requests in parallel.

Some shared state, e.g. hit counts:

- each thread increments a shared counter to track number of hits

```
…
hits = hits + 1;
…
```

```
…
LW R0, hitsloc
ADDI R0, r0, 1
SW R0, hitsloc
…
```

What happens when two threads execute concurrently?

Assume hits starts at 0 and 10 clients.

What is ***not*** a possible value for hits?

A) 10

B) 8

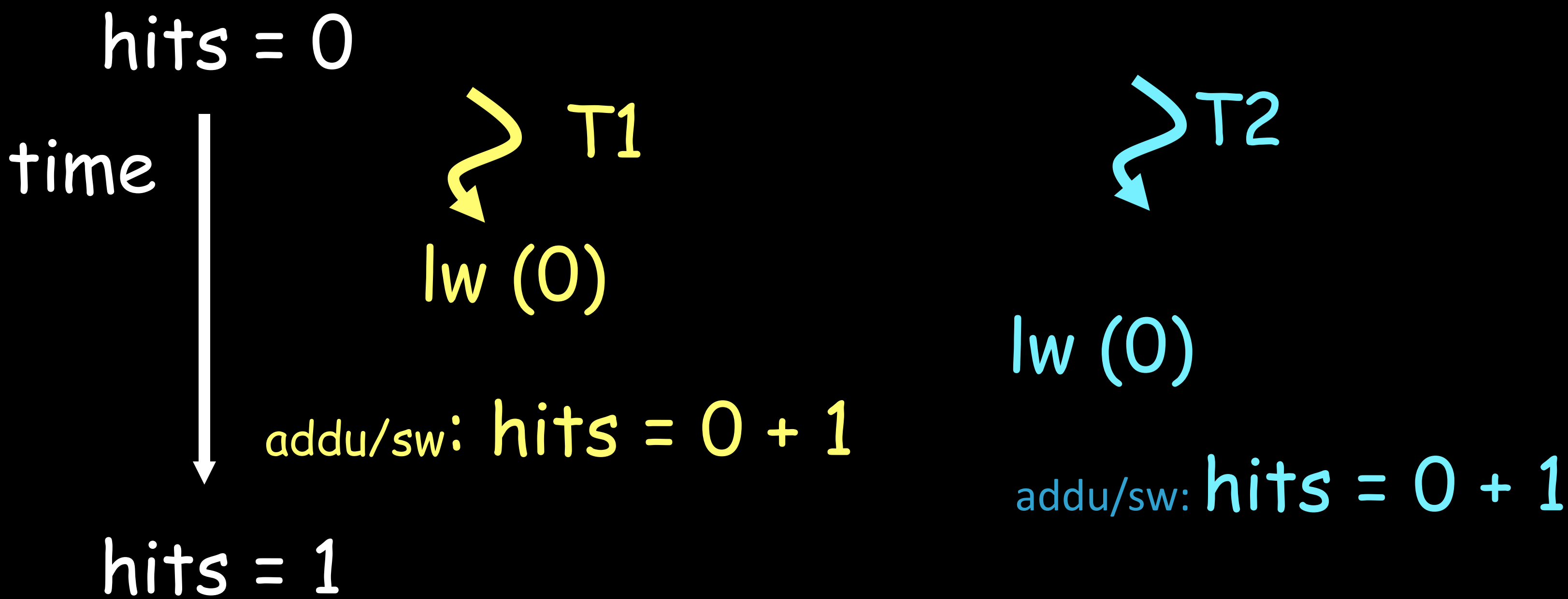
C) 5

D) 1

E) 0

Shared counters

Possible result: lost update!



Timing-dependent failure ⇒ race condition

- hard to reproduce ⇒ Difficult to debug

Race conditions

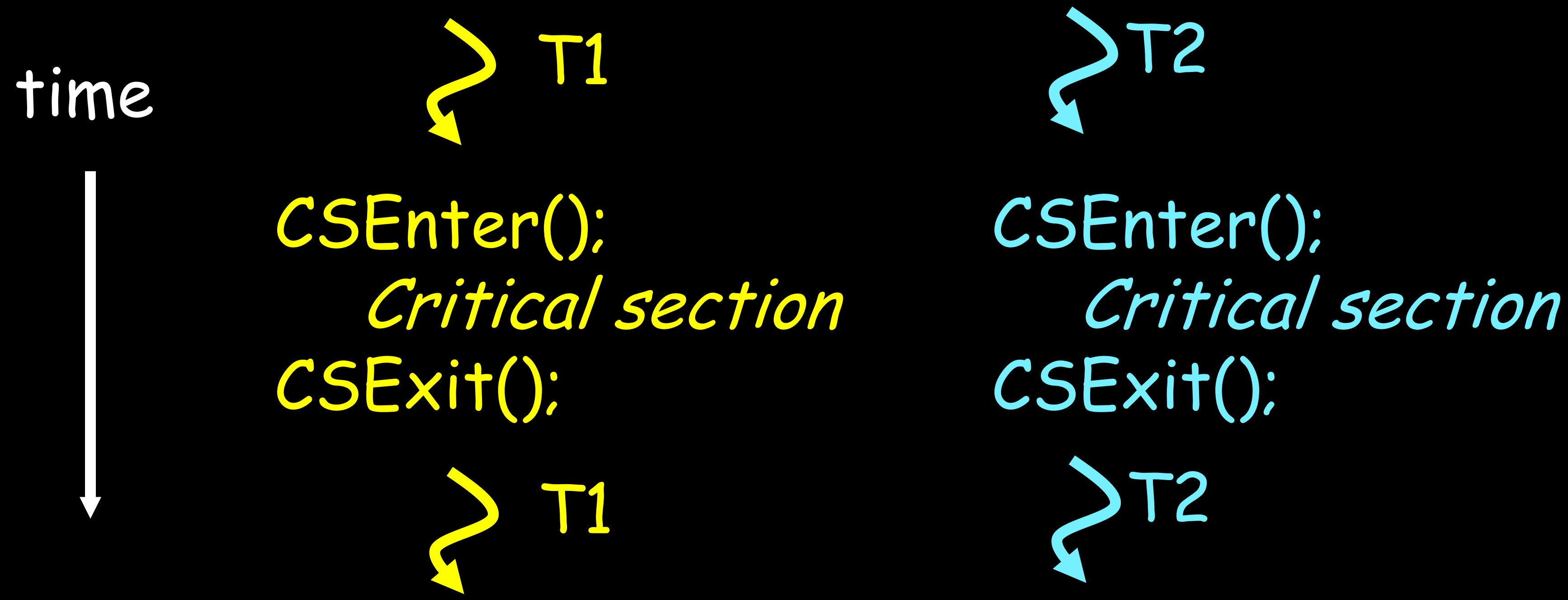
Def: timing-dependent error involving access to shared state

- Whether it happens depends on how threads scheduled: who wins “races” to instruction that updates state vs. instruction that accesses state
- Races are intermittent, may occur rarely
  - Timing dependent = small changes can hide bug
- A program is correct *only* if *all possible* schedules are safe
  - Number of possible schedule permutations is huge
  - Need to imagine an adversary who switches contexts at the worst possible time

Critical sections

To eliminate races: use *critical sections* that only one thread can be in

- Contending threads must wait to enter



Mutexes

Critical sections typically associated with mutual exclusion locks (*mutexes*)

Only one thread can hold a given mutex at a time

Acquire (lock) mutex on entry to critical section

- Or block if another thread already holds it

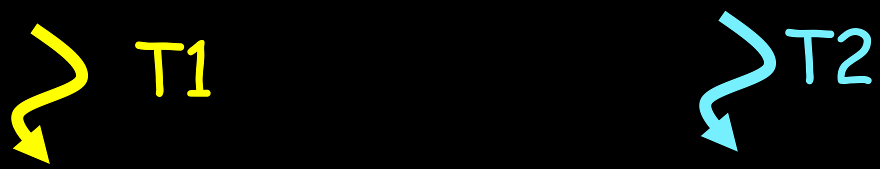
Release (unlock) mutex on exit

- Allow one waiting thread (if any) to acquire & proceed

```
pthread_mutex_init(&m);
```

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

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



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)
}
```

Hardware Support for Synchronization

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 swap (to test/set lock variable)

```
try: MOVE $t0,$s4     ;copy exchange value
     LL   $t1,0($s1)  ;load linked
     SC   $t0,0($s1)  ;store conditional
     BEQZ $t0,try     ;branch store fails
     MOVE $s4,$t1     ;put load value in $s4
```

Mutex from LL and SC

Linked load / Store Conditional

m = 0 - free   1 - locked

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

set

```
int test_and_set(int *m) {
  old = *m;      ] LL
  *m = 1;        ] SW
  return old;
}
```

atomic

Mutex from LL and SC

Linked load / Store Conditional

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

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

```
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

```
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)
}
```

Spin waiting

Spin lock

Alternative Atomic Instructions

Other atomic hardware primitives

- test and set (x86)
- atomic increment (x86)
- bus lock prefix (x86)

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, …)

very expensive

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

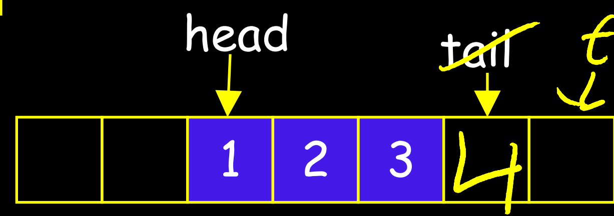
Using synchronization primitives to build concurrency-safe datastructures

Broken invariants

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++;
}
```

$t = (t+1) \% n$

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

$h = (h+1) \% n$

Need synchronization

Protecting an invariant

```
// invariant: (protected by 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++;
  pthread_mutex_unlock(m);
}
```

BUG

Can't wait while holding lock

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

Rule of thumb: all 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!

Cache Coherency

causes yet more trouble

Remember: Cache Coherence

Recall: Cache coherence defined...

Informal: Reads return most recently written value

Formal: For concurrent processes P_1 and P_2

- P writes X before P reads X (with no intervening writes)
  $\Rightarrow$ read returns written value
- P_1 writes X before P_2 reads X
  $\Rightarrow$ read returns written value
- P_1 writes X and P_2 writes X
  $\Rightarrow$ all processors see writes in the same order
  - all see the same final value for X

Relaxed consistency implications

Ideal case: sequential consistency

- Globally: writes appear in interleaved order
- Locally: other core's writes show up in program order

In practice: not so much…

- write-back caches → sequential consistency is tricky
- writes appear in semi-random order
- locks alone don't help

* MIPS has sequential consistency; Intel does not

Acquire/release

Memory Barriers and Release Consistency

- Less strict than sequential consistency; easier to build

One protocol:

- Acquire: lock, and force subsequent accesses after
- Release: unlock, and force previous accesses before

```
P1: ...
    acquire(m);
    A[t] = c;
    t++;
    release(m);
```

```
P2: ...
    acquire(m);
    A[t] = c;
    t++;
    unlock(m);
```

Moral: can't rely on sequential consistency
(so use synchronization libraries)

Are Locks + Barriers enough?

Beyond mutexes

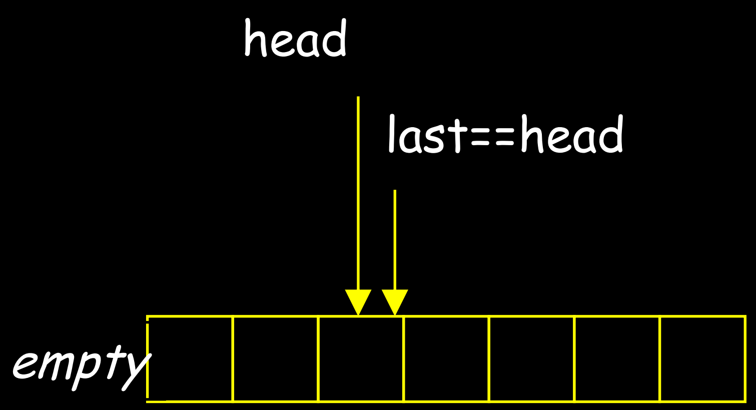
Writers must check for full buffer

& Readers must check if for empty buffer

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

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

while(empty) {}



Beyond mutexes

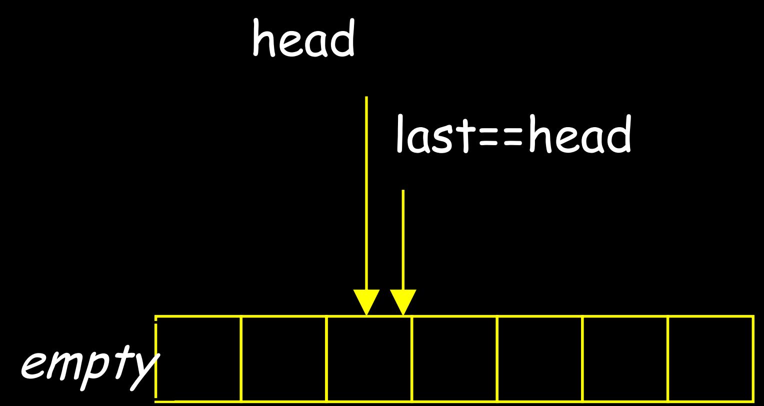
Writers must check for full buffer

& 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++;
  release(L);
  return c;
}
```

empty condition may no longer hold in critical section



Dilemma: Have to check while holding lock,

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++;
  release(L);
  return c;
}
```

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

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++;
      }
      release(L);
  } while (empty);
  return c;
}
```

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

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, ...

Administrivia

Pizza party: PA3 Games Night

- Friday, April 27th, 5:00-7:00pm
- Location: Upson B17

Prelim3 Review

- Today, Tuesday, April 24th, 5:30-7:30pm
- Location: Hollister 110

Prelim 3

- Thursday, April 26th, 7:30pm
- Location: Olin 155

PA4: Final project out next week

- Demos: May 14-16
- ***Will not be able to use slip days***