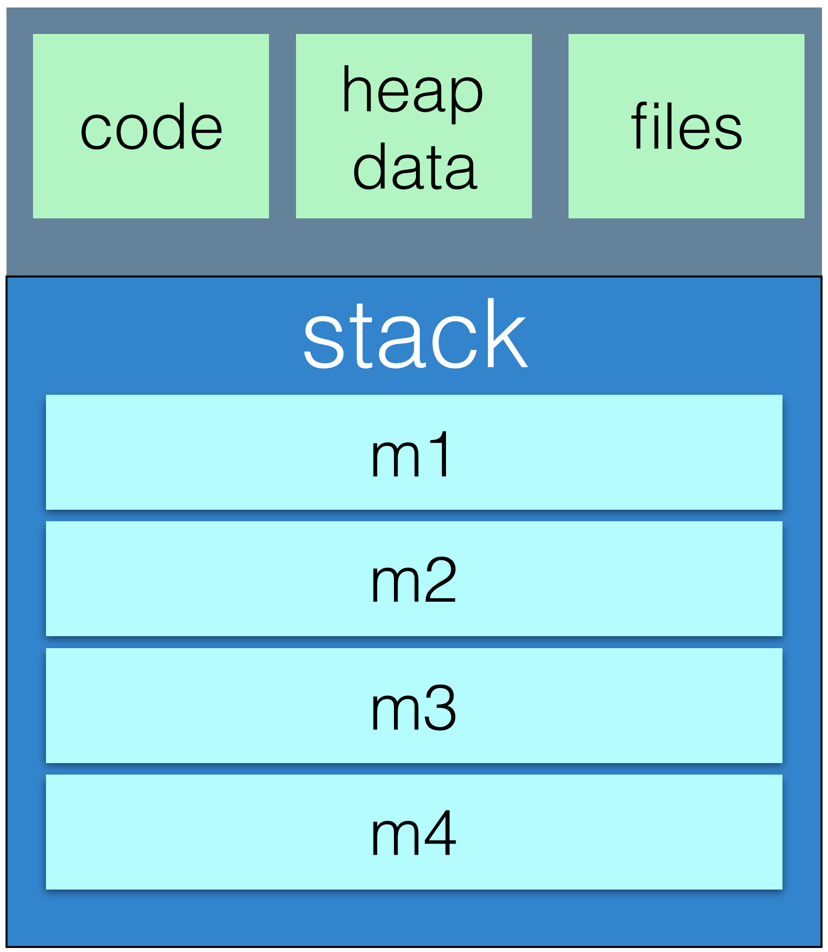
Synchronization

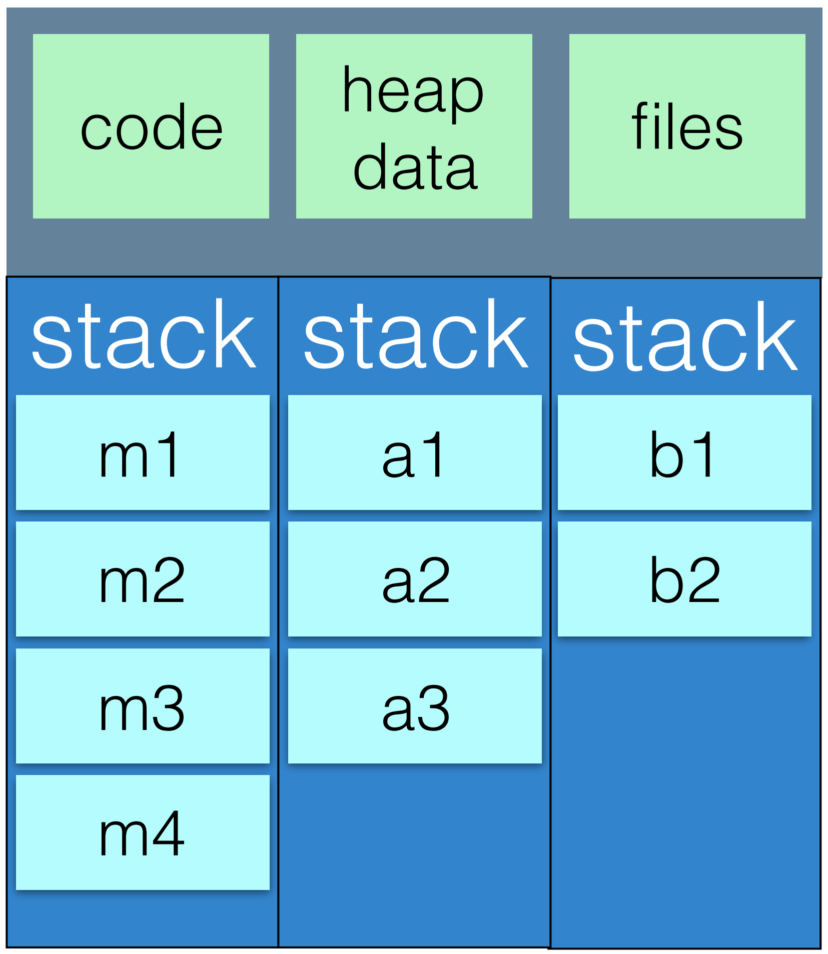
CS 475, Spring 2018
Concurrent & Distributed Systems

GEORGE MASON UNIVERSITY

Review: Threads: Memory View



Single-Threaded Process



Multi-Threaded Process

Each thread might be executing totally different code, too

Review: Race Conditions

```
static int i = 0;
public static void increment()
{
    i = i + 1;
}
```

Thread 1	Thread 2
increment()	increment()
read i = 0	
write i = 1	read i = 0
	write i =1

Review: Critical Section in increment()

```java
static int i = 0;
public static void increment()
{
    enterSection();
    i = i + 1;
    exitSection();
}
```

Only one thread can read/write i at once

But how to implement enterSection() and exitSection()?

Announcements

- Additional readings:
  - OS TEP Ch 28.1-28.4; Ch 31
- Reminder: HW1 is due 2pm on Weds

Critical Section Problem

- Each thread/process has some *critical section* of code that:
  - Changes shared variables, files etc
  - When one thread/process is in a critical section, no other may be in the same critical section
- Critical section problem: design a protocol to solve this
- Each process/thread asks for permission to enter critical section, does its work, then exits the section

Solution to Critical-Section Problem

- Need to guarantee **mutual exclusion**
  - If one thread/process is executing its critical section, no other can execute in their critical sections
- Need to guarantee **progress:**
  - If no process is executing in its critical section, and some other would like to, then some process must be allowed to continue
- Need to guarantee **bounded waiting:**
  - If some process wants to enter its critical section, it must eventually be granted access

Peterson's Solution

- Simple algorithm that solves critical section problem
- Requires two variables: **int turn**, **boolean flag[]**
- **turn** indicates which process can enter the critical section
- **flag** is an array indicating which process is ready to enter its critical section, **flag[i] = true** means P_i is ready to enter its critical section

Peterson's Solution

Algorithm for P_i

```
while(true) {
    flag[i] = true;
    turn = j;
    while(flag[j] && turn == j); //wait if j is in its critical section
    //critical section
    flag[i] = false; //signal we are done
    //do anything else that is not in critical section
}
```

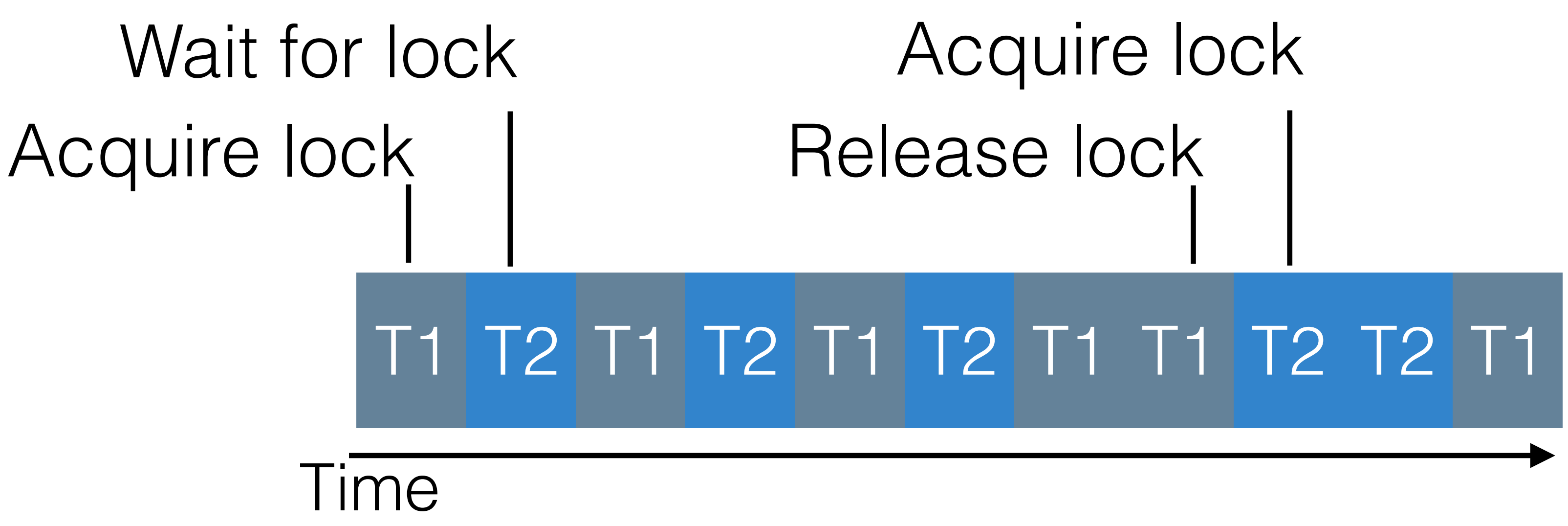
"Busy waiting"

Problem: Inefficient - this thread keeps checking flag[], preventing other things from running on your CPU

Sidebar: tough to do correctly on modern hardware, e.g. JVM (Double Checked Locking Manifesto)

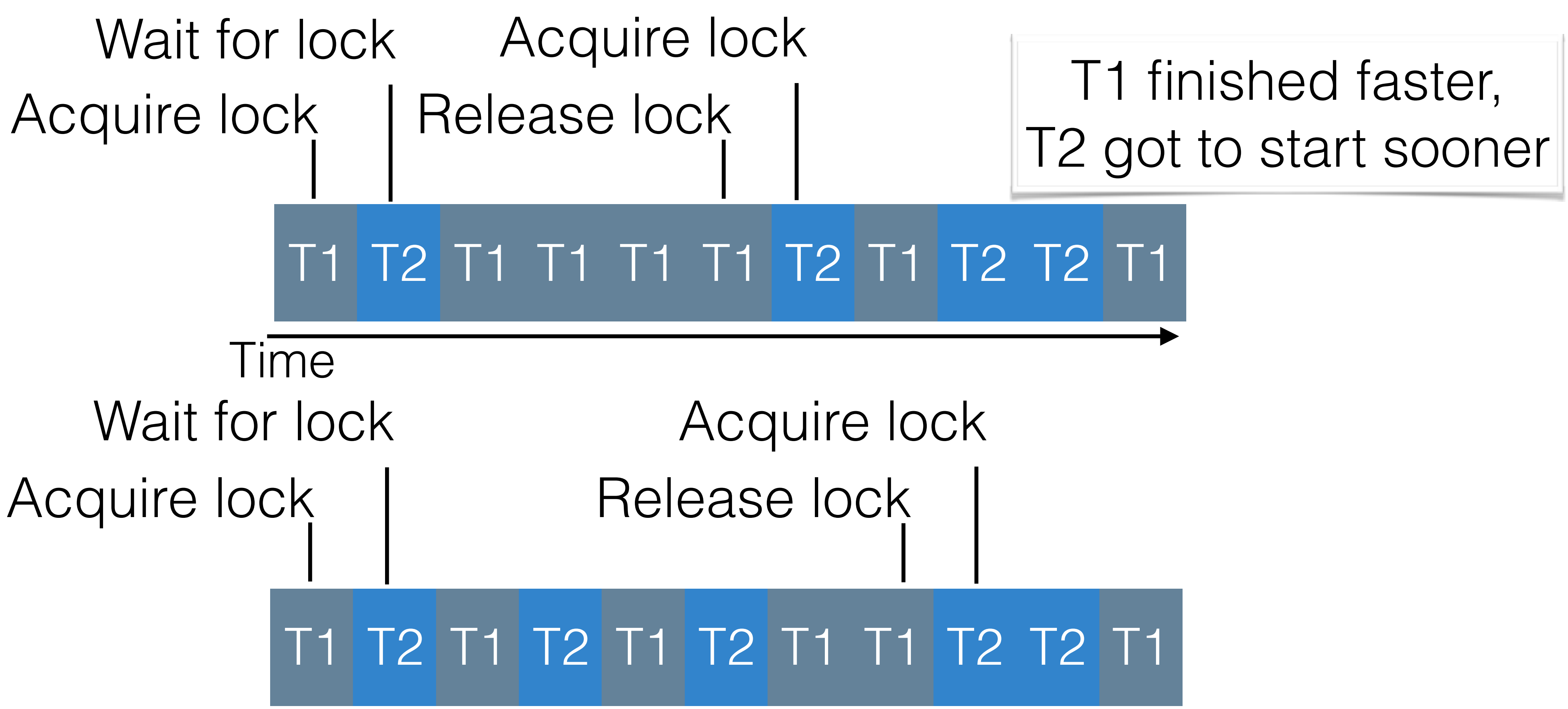
Busy Waiting

```
while(true) {
    flag[i] = true;
    turn = j;
    while(flag[j] && turn == j); //wait if j is in its critical section
    //critical section
    flag[i] = false; //signal we are done
    //do anything else that is not in critical section
}
```



Locks

- Most systems have some hardware support for implementing this, based on **locks**
- This tells the OS and processor that when a thread is waiting for a lock, **not to bother running it** until it can receive the lock



Mutex Locks

- Previous solutions are complicated and generally inaccessible to application programmers
- OS designers build software tools to solve critical section problem
- Simplest is mutex lock
- Protect a critical section by first acquire() a lock then release() the lock
- Calls to acquire() and release() must be atomic
- Usually implemented via hardware atomic instructions
- Ideally: automatically sleeps calling thread if not available
- Otherwise, called a spinlock

Semaphores

- Synchronization tool that provides more sophisticated ways (than Mutex locks) for process to synchronize their activities.
- Semaphore S – integer variable
- Can only be accessed via two indivisible (atomic) operations
- wait(): consumes a resource (once available)
- signal(): release a resource

Sempahores

- Counting semaphore – integer value can range over an unrestricted domain
- Binary semaphore – integer value can range only between 0 and 1
  - Same as a mutex lock
- Can solve various synchronization problems

Semaphores

- Define a semaphore as a record:

```
typedef struct {
int value;
       struct process *L;
    } semaphore;
```

- Assume two simple operations provided by OS:
  - block suspends the process that invokes it.
  - wakeup(P) resumes the execution of a blocked process P.

Semaphores

- Implementation of wait and signal. Starting value is # of permits

```
wait(S):
    S.value--;
    if (S.value < 0) {
        enqueue(this,S.L);
        block();
    }

signal(S):
    S.value++;
    if (S.value <= 0) {
        Thread toWake = pop(s.L);
        wakeup(toWake);
}
```

Deadlocks & Starvation

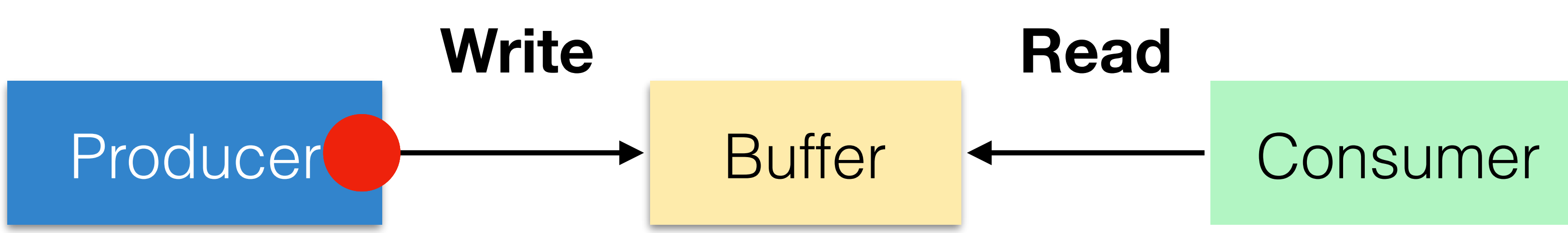
- Starvation: one or more threads are blocked from gaining access to a resource, and hence, can't make progress
- Deadlock: Two or more threads are waiting for the others to do something
  - T1: Has lock 1, needs lock 2
  - T2: Has lock 2, needs lock 1
  - Hence, neither T1 nor T2 can execute

Classical Problems of Synchronization

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem

Bounded Buffer

- Producer/consumer communicating through a buffer that holds **n** items
- Producer can't put too many items in at one time, consumer can't remove if no items there
- Might have multiple producers, consumers



Example: buffer can only hold 2 items

Bounded Buffer

- What needs to be tracked?
  - Number of items in buffer
  - Which threads are waiting to put into buffer
  - Which threads are waiting to pull out of buffer

Bounded Buffer with Semaphores

- Semaphore **mutex** initialized to the value 1
- Semaphore **full** initialized to the value 0
- Semaphore **empty** initialized to the value n

mutex =1	Makes sure buffer is viewed atomically
full = 0	Represents number of full slots, tracks threads waiting to add more (if totally full)
empty = n	Represents number of empty slots, tracks threads waiting to read (if empty)

Bounded Buffer Pseudocode

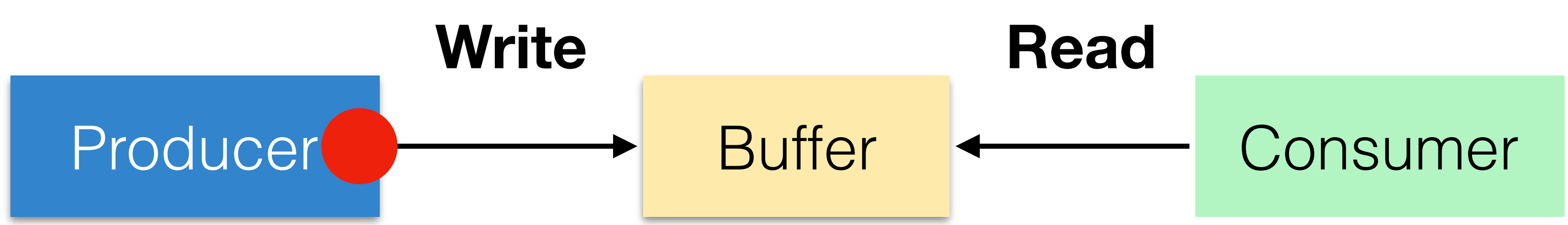
Producer

```
do {
    /* produce an item in next_produced */
    wait(empty);
    wait(mutex);
    /* add next produced to the buffer */
    signal(mutex);
    signal(full);
} while (true);
```

Consumer

```
do {
    wait(full);
    wait(mutex);
    /* remove an item from buffer to next_consumed */
    signal(mutex);
    signal(empty);
    /* consume the item in next consumed */
} while (true);
```

Bounded Buffer Example



Example: buffer can only hold 2 items

mutex = **0** — Makes sure buffer is viewed atomically

full = **2** — Represents number of full slots, tracks threads waiting to add more (if totally full)

empty = **0** — Represents number of empty slots, tracks threads waiting to read (if empty)

Readers and Writers Problem

- Commonly called a read-write lock: data can be read by an unlimited number of threads at a time, written by at most one
- If a thread wants to write, nobody else can be reading
- High level approach:
  - Semaphore used to guard writing
  - Integer variable used to track number of readers
  - First reader acquires write semaphore, last reader to finish releases it

Readers + Writers with Semaphores

- Semaphore **rw_mutex** initialized to 1
- Semaphore **mutex** initialized to 1
- Integer **read_count** initialized to 0

rw_mutex =1	Guards writing
read_count=0	Tracks number of clients reading
mutex = 1	Guards updates to read_count

Readers Writers Pseudocode

Writer

```
do {
   wait(rw_mutex);
  /* writing is performed */
  signal(rw_mutex);
} while (true);
```

Readers

```
do {
      wait(mutex);
      read_count++;
      if (read_count == 1)
            wait(rw_mutex);
      signal(mutex);
      /* reading is performed */
      wait(mutex);
      read count--;
      if (read_count == 0)
            signal(rw_mutex);
      signal(mutex);
} while (true);
```

Readers + Writers Example

Reader

First to arrive, set rw_mutex=0
Increment read_count

Decrement read_count

Reader

Increment read_count

Decrement read_count

Reader

Increment read_count

Decrement read_count, Released rw_mutex

Writer

Blocked: Unable to acquire rw_mutex

Holds rw_mutex

rw_mutex = 0 *Waiting: writer* — Guards writing

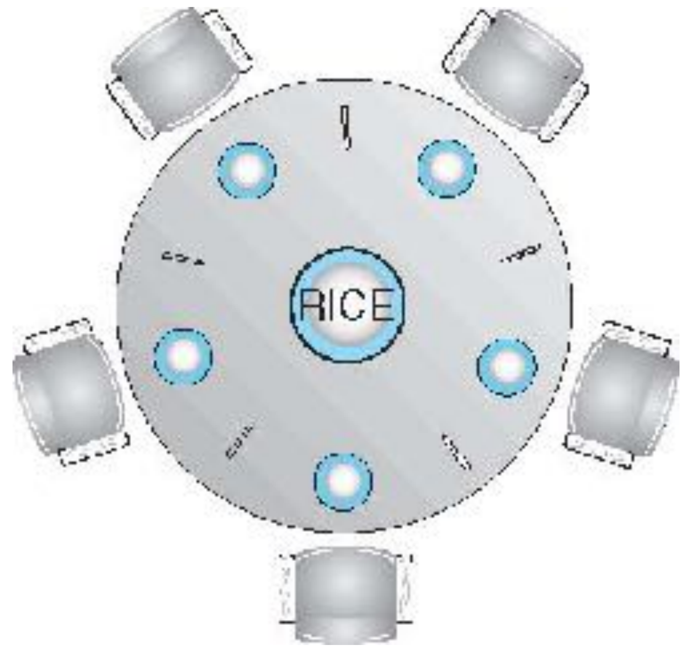
read_count= 3 — Tracks number of clients reading

mutex = 0 — Guards updates to read_count

Readers + Writers with Semaphores

- Might lead to starvation
  - As long as there is at least one thread reading, new readers will take priority over a waiting writer
- OS typically provides read/write locks to solve this

Dining Philosophers



- Philosophers spend their lives alternating thinking and eating
- Don't interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
- Need both to eat, then release both when done
- In the case of 5 philosophers
- Shared data
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1

Dining Philosophers Solution

- Each philosopher does this:

```
do {
    wait (chopstick[i] );
    wait (chopStick[ (i + 1) % 5] );
    //  eat
    signal (chopstick[i] );
    signal (chopstick[ (i + 1) % 5] );
    //  think
} while (TRUE);
```

- What is the problem with this solution?

Dining Philosophers Solution

- Resolving the deadlock in prior algorithm:
  - Allow at most 4 philosophers to be sitting simultaneously at the table.
  - Allow a philosopher to pick up the forks only if both are available (picking must be done in a critical section.
  - Use an asymmetric solution -- an odd-numbered philosopher picks up first the left chopstick and then the right chopstick. Even-numbered philosopher picks up first the right chopstick and then the left chopstick.

High-level synchronization mechanisms

- Semaphores are a very powerful mechanism for process synchronization, but they are a low-level mechanism
- Several high-level mechanisms that are easier to use have been proposed
- Monitors (Condition variables and locks)
- Read/Write Locks
- Java and Pthreads provide both semaphores and high-level synchronization mechanisms
- NOTE: high-level mechanisms easier to use but equivalent to semaphores in power

Locking in Java

- Most locks are *reentrant*: if you hold it, and ask for it again, you don't have to wait (because you already have it)
- Basic primitives:
  - synchronized{}
  - wait
  - notify
- Plus…
  - Lock API… lock.lock(), lock.unlock()
  - The *preferred* way

Synchronized methods in Java

```
public synchronized static void increment()
{
    i = i + 1;
}
```

Result: Before entering **increment()**, thread gets a lock on the Class object of **increment()**

wait and notify()

- Two mechanisms to enable coordination between multiple threads using the same monitor (target of synchronized)
- While holding a monitor on an object, a thread can **wait** on that monitor, which will temporarily release it, and put that thread to sleep
- Another thread can then acquire the monitor, and can **notify** a waiting thread to resume and re-acquire the monitor

wait and notify() example

Only one thread can be in put or take of the same queue

```
public class BlockingQueue<T> {

    private Queue<T> queue = new LinkedList<T>();
    private int capacity;

    public BlockingQueue(int capacity) {
        this.capacity = capacity;
    }

    public synchronized void put(T element) throws InterruptedException {
        while(queue.size() == capacity) {
            wait();
        }

        queue.add(element);
        notify(); // notifyAll() for multiple producer/consumer threads
    }

    public synchronized T take() throws InterruptedException {
        while(queue.isEmpty()) {
            wait();
        }

        T item = queue.remove();
        notify(); // notifyAll() for multiple producer/consumer threads
        return item;
    }
}
```

Synchronized methods in Java

```
public synchronized static void increment()
{
    i = i + 1;
}
```

Result: Before entering **increment()**, thread gets a lock on the Class object of **increment()**

```
public synchronized static void incrementOther()
{
    j = j + 1;
}
```

Result: Before entering **incrementOther()**, thread gets a lock on the Class object of **incrementOther()**

Problem?

Synchronized blocks in Java

- Can also use *any* object as that monitor

```
static Object someObject = new Object();
public static void increment()
{
    synchronized(someObject){
        i = i + 1;
    }
}
static Object someOtherObject = new Object();
public static void incrementOther()
{
    synchronized(someOtherObject){
        j = j + 1;
    }
}
```

Now, two different threads could call **increment()** and **incrementOther()** at the same time

Assignment 1 Discussion

- http://www.jonbell.net/gmu-cs-475-spring-2018/homework-1/
- https://autolab.cs.gmu.edu/courses/CSTEST/assessments

Roadmap

- Weds: Java Concurrency
  - Joke (didn't make it out last week):

    Knock, knock.
    Race condition.
    Who’s there?

Checkpoint

Go to socrative.com and select “Student Login” (works well on laptop, tablet or phone)

Room Name: CS475

ID is your @gmu.edu email

Remember: this is a checkpoint for you, it is only graded for attendance