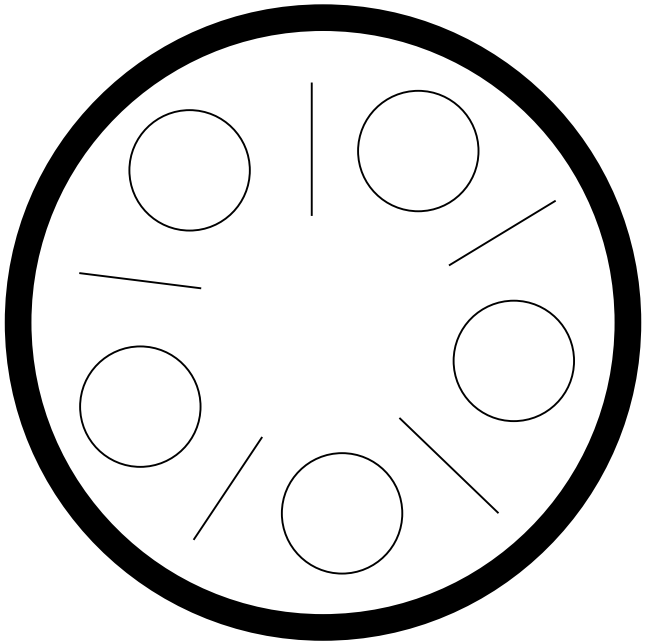
Dining Philosophers

Dining Philosophers

N philosophers are sitting at a table with N chopsticks, each needs two chopsticks to eat, and each philosopher alternates between thinking, getting hungry, and eating.



Dining Philosophers: Solution

```
do forever:
    think
    get hungry
    down(chopstick[i])
    down(chopstick[(i+1) % N])

    eat

    up(chopstick[i])
    up(chopstick[(i+1) % N])
```

Does this solution work?

A. Yes
B. No

Deadlock

Bringing It All Together

- Processes
  - Abstraction for protection
  - Define address space
- Threads
  - Share (and communicate) through global and static data, share the heap, each has its own stack and full use of the registers
  - Race conditions may be a problem!
- CPU Schedulers
  - May pre-empt a process or thread at any time
- Solving race conditions (Ensuring correctness)
  - Safety and liveness
  - Atomic instructions
  - Synchronization: mutual exclusion
  - Locks! Semaphores!

Producers/Consumers

```
Semaphore mutex = 1    //access to buffer
Semaphore empty = N    //count of empty slots
Semaphore full = 0     //count of full slots
int buffer[N]
```

```
BoundedBuffer::Producer(){
  <produce item>
  empty->Down() //get empty spot
  mutex->Down() //get access to buffer

  <add item to buffer>

  mutex->Up() //release buffer
  full->Up() //another item in buffer
}
```

```
BoundedBuffer::Consumer(){
  full->Down()    //get item
  mutex->Down() //get access to buffer

  <remove item from buffer>

  mutex->Up() //release buffer
  empty->Up() //another empty slot
  <use item>
}
```

Let's make a small change...

```
Semaphore mutex = 1    //access to buffer
Semaphore empty = N    //count of empty slots
Semaphore full = 0     //count of full slots
int buffer[N]
```

```
BoundedBuffer::Producer(){
  <produce item>
  empty->Down() //get empty spot
  mutex->Down() //get access to buffer

  <add item to buffer>

  mutex->Up() //release buffer
  full->Up() //another item in buffer
}
```

```
BoundedBuffer::Consumer(){
  mutex->Down() //get access to buffer
  full->Down()    //get item

  <remove item from buffer>

  mutex->Up() //release buffer
  empty->Up() //another empty slot
  <use item>
}
```

What is Deadlock?

- *Deadlock* occurs when two or more threads are waiting for an event that can only be generated by these same threads
- Deadlock is not starvation
  - Starvation can occur without deadlock
    - occurs when a thread waits indefinitely for some resources, but other threads are actually using it
  - But deadlock does imply starvation
- We will be discussing how deadlock can occur in the multi-threaded (or multiprocess) code we write (there are other places deadlock may occur)

Conditions for Deadlock

Deadlock occurs when **all** of the following conditions hold:

1. **Mutual Exclusion**: at least one thread must hold a resource in non-sharable mode
2. **Hold and Wait**: at least one thread holds a resources and is waiting for other resources to become available. A different thread holds the resource.
3. **No Pre-emption**: a thread only releases a resource voluntarily; another thread or the OS cannot force the thread to release the resource
4. **Circular Wait**: A set of waiting threads $\{t_1, \ldots, t_n\}$ where t_i is waiting on t_{i+1} ($i=1$ *to* n) and t_n is waiting on t_1

Deadlock Prevention

Prevent deadlock by insuring that at least one of the necessary conditions doesn't hold

1. **Mutual Exclusion**: make resources sharable
2. **Hold and Wait**: guarantee a thread cannot hold one resource when it requests another (or must request all at once)
3. **No Pre-emption**: If a thread requests a resource that cannot be immediately allocated to it, then the OS pre-empts all the resources the thread is currently holding. Only when all the resources are available will the OS restart the thread
4. **Circular Wait**: Impose an ordering on the locks and request them in order

Deadlock Prevention: Lock Ordering

- Order all locks
- All code grabs locks in a predefined order
- Complications:
  - Maintaining global order is difficult in a large project
  - Global order can force a client to grab a lock earlier than it would like, tying up the lock for longer than necessary

Monitors

Problems with Semaphores

- Huge step up from what we had, but…
- Essentially shared global variables
- Too many purposes
  - Waiting for a condition is independent of mutual exclusion
- No control or guarantee of proper usage
- Difficult to read (and develop) code
- Not typically used in new *user* code
  - Where are they used?
- So… *what do we use in user code?*

Monitors

- Encapsulate shared data
  - Collect related shared data into an object/module
    - Struct or File in C (logical encapsulation)
    - All data is private
- Allow operations on the shared data
  - Define functions for accessing the shared data
    - These are the critical sections
- Provide mutual exclusion
  - Associate a lock (exactly one!) with each object/module
  - Acquire the lock before executing any function
- Allow threads to synchronize in the critical section
  - Guarantees against deadlock
  - Has *condition variables* for this---more in a minute!

Monitors, Formally

A monitor defines a *lock* and zero or more *condition variables* for managing concurrent access to shared data.

- uses the *lock* to ensure that only a single thread is active in the monitor at any point
- the *lock* also provides mutual exclusion for shared data
- *Condition variables* enable threads to block waiting for an event inside of critical sections
  - release the lock at the same time the thread is put to sleep

Monitor Functions: Implementation

- Acquire the lock at the start of every function (first thing!)
  - Operate on the shared data
  - Temporarily release the lock if they can't complete due to missing resource (use condition variable for this)
  - Reacquire the lock when they can continue (again, condition variable!)
  - Operate on the shared data
- Release the lock at the end

```
 Semaphore mutex = 1    //access to buffer
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 int buffer[N]
```

```
BoundedBuffer::Producer(){
  <produce item>
  empty->down() //get empty spot
  mutex->down() //get access to buffer

  <add item to buffer>

  mutex->up() //release buffer
  full->up() //another item in buffer
}
```

Condition Variables

Condition Variables

- Enable threads to wait efficiently for changes to shared state protected by a lock
- Each one is a queue of waiting threads (no state!)
- Enable the thread to block inside a critical section by *atomically* releasing the Lock at the same time the thread is blocked

Rule: A thread *must* hold the lock when doing condition variable operations

Condition Variable Operations

1. Wait(Lock lock)
   - atomic (release lock, move thread to waiting queue, suspend thread)
   - when the thread wakes up it re-acquires the lock (before returning from wait)
   - thread will *always* block
2. Signal(Lock lock)
   - wake up waiting thread, if one exists. Otherwise, it's a no-op
3. Broadcast(Lock lock)
   - wake up all waiting threads, if any exist. Otherwise, it's a no-op

Monitor Operations

Lock->Acquire() //acquires lock, when returns, thread has lock
Lock->Release() //releases lock

CondVar::Wait(lock){

- *move thread to wait queue and suspend thread
- *release lock
- *on signal, wake up, re-acquire lock
- *return

}

CondVar::Signal(lock){

- *wake up a thread waiting on condVar
- *return

}

CondVar::Broadcast(lock){

- *wake up ALL threads waiting on condVar
- *return

}

*The pseudocode on this slide assumes Mesa/Hansen semantics (more in a minute)

Resource Variables and Signal Semantics

Resource Variables

- Conditions variables (unlike semaphores) keep no state
- Each condition variable should have a resource variable that tracks the state of that resource
  - *You must maintain this variable*
- Check the resource variable before calling wait on the associated condition variable to ensure the resource really *isn't* available
- Once the resource is available, claim it (subtract the amount you are using!)
- Before signaling that you are finished with a resource, indicate the resource is available by increasing the resource variable

Signal() Semantics

Which thread executes once signal() is called?

- If there are no waiting threads, the signaler continues and the signal is effectively lost
- If there is a waiting thread (or two):
  - There are at least two ready threads: the one that called signal() and the one that was (or will be) awakened
  - Exactly one of the threads can execute or we will have more than one thread active in the monitor (violates mutual exclusion!)
  - So which thread gets to execute?

Whose turn is it?

Mesa/Hansen Style

- The thread that signals keeps the lock (and thus the processor)
- The waiting thread waits for the lock
  - Signal is only a hint that the condition may be true: shared state may have changed!
  - Adding signals affects performance, but never safety
- Implemented in Java and most real operating systems

Hoare Style

- The thread that signals gives up the lock and the waiting thread gets the lock
  - Signaling is atomic with the resumption of the waiting thread
  - Shared state cannot change before waiting thread is resumed
- When the thread that was waiting and is now executing exits or waits again, it releases the lock back to the signaling thread
- Implemented in most textbooks (not yours!)

More on Turns

- With Mesa-style, waiting thread may need to wait again after it is wakened (Why?), so *while* is important
- With Hoare-style, we can change *while* to *if* because a waiting thread runs immediately

```
public void remove(){
  lock->Acquire()
  while (queue_size <= 0){
    full->wait(lock);
  }
  queue_size--;
  remove item;
  lock->Release();
}
```

Regardless, if you assume there is NO atomicity between signal() and the return from wait(), your code will always work.

Signal vs. Broadcast

- It is always safe to use broadcast() instead of signal()
  - only performance is affected
- signal() is preferable when
  - at most one waiting thread can make progress
  - any thread waiting on the condition variable can make progress
- broadcast() is preferable when
  - multiple waiting threads may be able to make progress
  - the same condition variable is used for multiple predicates
    - some waiting threads can make progress, others can’t

Question

Every monitor function should begin with what command?

A. Wait()
B. Signal()
C. Lock->Acquire()
D. Lock->Release()
E. Broadcast()

Question

When using monitors, you should:

A. Call wait() to determine resource availability AND block if the resource is unavailable
B. Call wait() in an if statement that checks resource availability
C. Call wait() in a while loop that checks resource availability

Comparing Monitors and Semaphores

Semaphore Example: Producers/Consumers (Recall)

```
Semaphore mutex = 1    //access to buffer
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int buffer[N]

BoundedBuffer::Consumer(){
  full->down()     //get item
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  <use item>
}
```