CS 333
Introduction to Operating Systems

Class 6 – Monitors and Message Passing

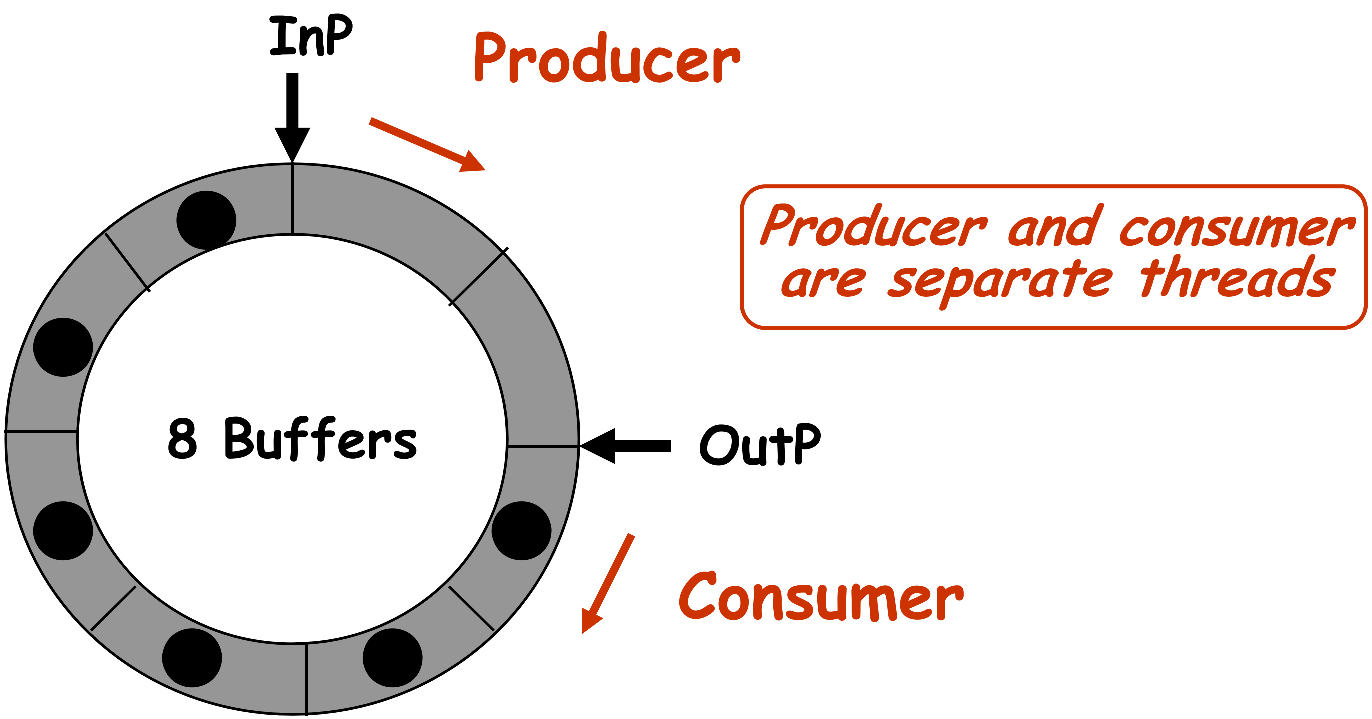
Jonathan Walpole
Computer Science
Portland State University

But first …

- Continuation of Class 5 – Classical Synchronization Problems

Producer consumer problem

- Also known as the bounded buffer problem



Does this solution work?

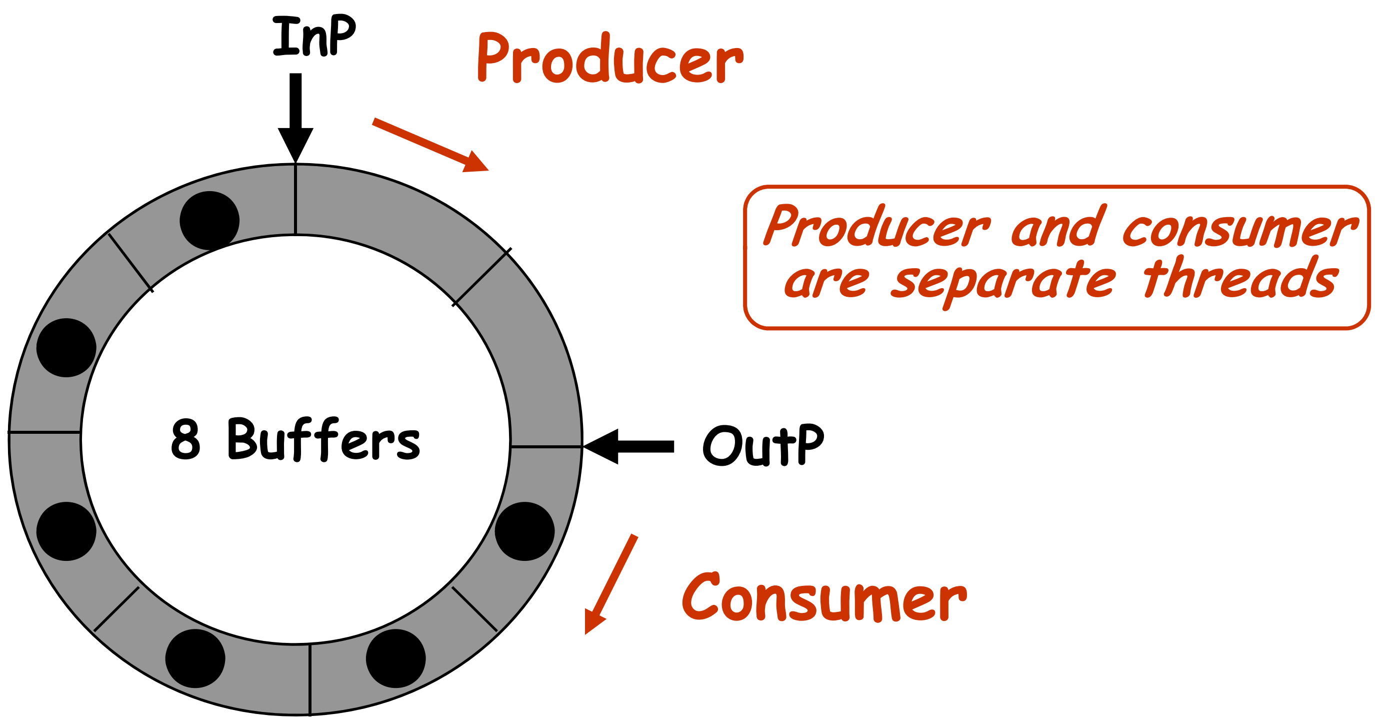
```
Global variables
  semaphore full_buffs = 0;
  semaphore empty_buffs = n;
  char buff[n];
  int InP, OutP;
```

```
thread producer {
  while(1){
    // Produce char c...
    down(empty_buffs)
    buf[InP] = c
    InP = InP + 1 mod n
    up(full_buffs)
  }
}
```

```
thread consumer {
  while(1){
    down(full_buffs)
    c = buf[OutP]
    OutP = OutP + 1 mod n
    up(empty_buffs)
    // Consume char...
  }
}
```

Producer consumer problem

- What is the shared state in the last solution?
- Does it apply mutual exclusion? If so, how?

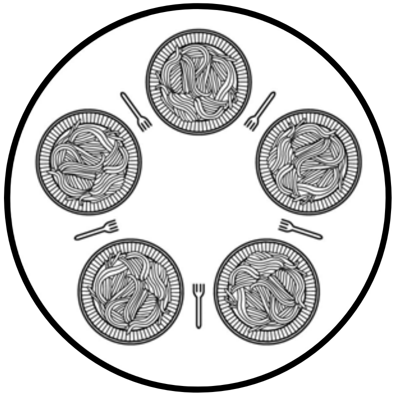


Problems with solution

- **What if we have multiple producers and multiple consumers?**
  - Producer-specific and consumer-specific data becomes shared
  - We need to define and protect critical sections

Dining philosophers problem

- Five philosophers sit at a table
- One fork/chopstick between each philosopher – need two to eat



Each philosopher is modeled with a thread

```
while(TRUE) {
  Think();
  Grab first fork;
  Grab second fork;
  Eat();
  Put down first fork;
  Put down second fork;
}
```

- *Why do they need to synchronize?*
- *How should they do it?*

Is this a valid solution?

```
#define N 5

Philosopher() {
  while(TRUE) {
    Think();
    take_fork(i);
    take_fork((i+1)% N);
    Eat();
    put_fork(i);
    put_fork((i+1)% N);
  }
}
```

Problems

- **Holding one fork while you wait for the other can lead to deadlock!**
  - You should not hold on to a fork unless you can get both
  - Is there a deterministic, deadlock-free, starvation-free solution to doing this?

Working towards a solution …

```
#define N 5

Philosopher() {
  while(TRUE) {
    Think();
    take_fork(i);
    take_fork((i+1)% N);
    Eat();
    put_fork(i);
    put_fork((i+1)% N);
  }
}
```

take_forks(i)

put_forks(i)

Working towards a solution …

```
#define N 5

Philosopher() {
  while(TRUE) {
    Think();
    take_forks(i);
    Eat();
    put_forks(i);
  }
}
```

Picking up forks

```
int state[N]
semaphore mutex = 1
semaphore sem[i]
```

```
take_forks(int i) {
  wait(mutex);
  state [i] = HUNGRY;
  test(i);
  signal(mutex);
  wait(sem[i]);
}
```

```
// only called with mutex set!

test(int i) {
 if (state[i] == HUNGRY &&
     state[LEFT] != EATING &&
     state[RIGHT] != EATING){
   state[i] = EATING;
   signal(sem[i]);
 }
}
```

Putting down forks

```
int state[N]
semaphore mutex = 1
semaphore sem[i]
```

```
put_forks(int i) {
  wait(mutex);
  state [i] = THINKING;
  test(LEFT);
  test(RIGHT);
  signal(mutex);
}
```

```
// only called with mutex set!

test(int i) {
 if (state[i] == HUNGRY &&
     state[LEFT] != EATING &&
     state[RIGHT] != EATING){
   state[i] = EATING;
   signal(sem[i]);
 }
}
```

Dining philosophers

- **Is the previous solution correct?**
- **What does it mean for it to be correct?**
- **How could you generate output to help detect common problems?**
  - What would a race condition look like?
  - What would deadlock look like?
  - What would starvation look like?

The sleeping barber problem

The sleeping barber problem

- ***Barber:***
  - While there are customers waiting for a hair cut put one in the barber chair and cut their hair
  - When done move to the next customer else go to sleep, until a customer comes in

- ***Customer:***
  - If barber is asleep wake him up for a haircut
  - If someone is getting a haircut wait for the barber to become free by sitting in a chair
  - If all chairs are all full, leave the barbershop

Designing a solution

- **How will we model the barber(s) and customers?**
- **What state variables do we need?**
  - .. and which ones are shared?
  - …. and how will we protect them?
- **How will the barber sleep?**
- **How will the barber wake up?**
- **How will customers wait?**
- **How will they proceed?**
- **What problems do we need to look out for?**

Is this a good solution?

```
const CHAIRS = 5
var customers: Semaphore
    barbers: Semaphore
    lock: Mutex
    numWaiting: int = 0
```

Barber Thread:

```
  while true
    Wait(customers)
    Lock(lock)
    numWaiting = numWaiting-1
    Signal(barbers)
    Unlock(lock)
    CutHair()
  endWhile
```

Customer Thread:

```
  Lock(lock)
  if numWaiting < CHAIRS
    numWaiting = numWaiting+1
    Signal(customers)
    Unlock(lock)
    Wait(barbers)
    GetHaircut()
  else  -- give up & go home
    Unlock(lock)
  endIf
```

The readers and writers problem

- **Multiple readers and writers want to access a database (each one is a thread)**

- **Multiple readers can proceed concurrently**
  - *No race condition if nobody is modifying data*

- **Writers must synchronize with readers and other writers**
  - *only one writer at a time !*
  - *when someone is writing, there must be no readers !*

Goals:

- Maximize concurrency.
- Prevent starvation.

Designing a solution

- **How will we model the readers and writers?**
- **What state variables do we need?**
  - .. and which ones are shared?
  - …. and how will we protect them?
- **How will the writers wait?**
- **How will the writers wake up?**
- **How will readers wait?**
- **How will the readers wake up?**
- **What problems do we need to look out for?**

Is this a valid solution to readers & writers?

```
var mut: Mutex = unlocked
    db: Semaphore = 1
    rc: int = 0
```

Writer Thread:

```
  while true
    ...Remainder Section...
    Wait(db)
    ...Write shared data...
    Signal(db)
  endWhile
```

Reader Thread:

```
  while true
    Lock(mut)
    rc = rc + 1
    if rc == 1
      Wait(db)
    endIf
    Unlock(mut)
    ... Read shared data...
    Lock(mut)
    rc = rc - 1
    if rc == 0
      Signal(db)
    endIf
    Unlock(mut)
    ... Remainder Section...
  endWhile
```

Readers and writers solution

- **Does the previous solution have any problems?**
  - is it “fair”?
  - can any threads be starved? If so, how could this be fixed?

Monitors

Monitors

- **It is difficult to produce correct programs using semaphores**
  - correct ordering of wait and signal is tricky!
  - avoiding race conditions and deadlock is tricky!
  - boundary conditions are tricky!

- **Can we get the compiler to generate the correct semaphore code for us?**
  - what are suitable higher level abstractions for synchronization?

Monitors

- **Related shared objects are collected together**
- **Compiler enforces encapsulation/mutual exclusion**
  - Encapsulation:
    - **Local data variables are accessible only via the monitor's entry procedures (like methods)**
  - Mutual exclusion
    - **A monitor has an associated mutex lock**
    - **Threads must acquire the monitor's mutex lock before invoking one of its procedures**

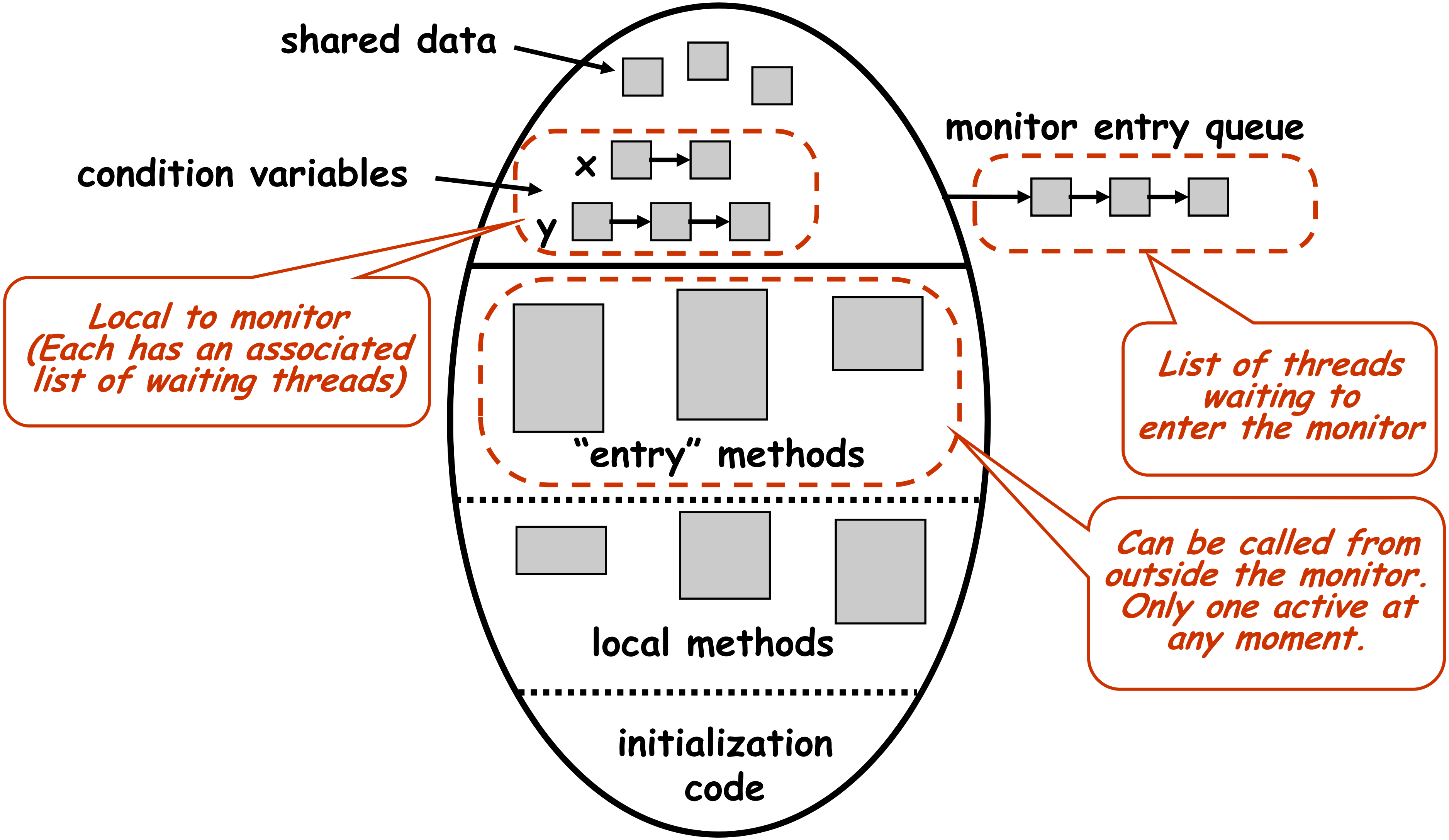
Monitors and condition variables

- **But we need two flavors of synchronization**
  - Mutual exclusion
    - **Only one at a time in the critical section**
    - **Handled by the monitor's mutex**
  - Condition synchronization
    - **Wait until a certain condition holds**
    - **Signal waiting threads when the condition holds**

Monitors and condition variables

- Condition variables (cv) for use within monitors
  - cv.wait(mon-mutex)
    - thread blocked (queued) until condition holds
    - Must not block while holding mutex!
    - monitor mutex must be released!
  - cv.signal()
    - signals the condition and unblocks (dequeues) a thread

Monitor structures



Monitor example for mutual exclusion

```
process Producer
begin
  loop
    <produce char "c">
    BoundedBuffer.deposit(c)
  end loop
end Producer
```

```
process Consumer
begin
  loop
    BoundedBuffer.remove(c)
    <consume char "c">
  end loop
end Consumer
```

```
monitor: BoundedBuffer
var  buffer : ...;
     nextIn, nextOut :... ;

  entry deposit(c: char)
     begin
       ...
     end

  entry remove(var c: char)
     begin
       ...
     end

end BoundedBuffer
```

Observations

- That's much simpler than the semaphore-based solution to producer/consumer (bounded buffer)!
- … but where is the mutex?
- … and what do the bodies of the monitor procedures look like?

Monitor example with condition variables

```
monitor : BoundedBuffer
var buffer                 : array[0..n-1] of char
    nextIn,nextOut         : 0..n-1 := 0
    fullCount              : 0..n   := 0
    notEmpty, notFull      : condition
```

```
entry deposit(c:char)
begin
  if (fullCount = n) then
      wait(notFull)
  end if

  buffer[nextIn] := c
  nextIn := nextIn+1 mod n
  fullCount := fullCount+1

  signal(notEmpty)
end deposit
```

```
entry remove(var c: char)
begin
  if (fullCount = n) then
    wait(notEmpty)
  end if

  c := buffer[nextOut]
  nextOut := nextOut+1 mod n
  fullCount := fullCount-1

  signal(notFull)
end remove
```

```
end BoundedBuffer
```

Condition variables

"Condition variables allow processes to synchronize based on some state of the monitor variables."

Condition variables in producer/consumer

"NotFull" condition

"NotEmpty" condition

- Operations Wait() and Signal() allow synchronization within the monitor
- When a producer thread adds an element...
  - A consumer may be sleeping
  - Need to wake the consumer... Signal

Condition synchronization semantics

- ***"Only one thread can be executing in the monitor at any one time."***
- **Scenario:**
  - Thread A is executing in the monitor
  - Thread A does a signal waking up thread B
  - What happens now?
  - Signaling and signaled threads can not both run!
  - … so which one runs, which one blocks, and on what queue?

Monitor design choices

- **Condition variables introduce a problem for mutual exclusion**
  - only one process active in the monitor at a time, so what to do when a process is unblocked on signal?
  - must not block holding the mutex, so what to do when a process blocks on wait?

Monitor design choices

- **Choices when A signals a condition that unblocks B**
  - A waits for B to exit the monitor or block again
  - B waits for A to exit the monitor or block
  - Signal causes A to immediately exit the monitor or block (… but awaiting what condition?)
- **Choices when A signals a condition that unblocks B & C**
  - B is unblocked, but C remains blocked
  - C is unblocked, but B remains blocked
  - Both B & C are unblocked … and compete for the mutex?
- **Choices when A calls wait and blocks**
  - a new external process is allowed to enter
  - but which one?

Option 1: Hoare semantics

- **What happens when a Signal is performed?**
  - signaling thread (A) is suspended
  - signaled thread (B) wakes up and runs immediately
- **Result:**
  - B can assume the condition is now true/satisfied
  - Hoare semantics give strong guarantees
  - Easier to prove correctness
- **When B leaves monitor, A can run.**
  - **A might resume execution immediately**
  - **... or maybe another thread (C) will slip in!**

Option 2: MESA Semantics (Xerox PARC)

- **What happens when a Signal is performed?**
  - the signaling thread (A) continues.
  - the signaled thread (B) waits.
  - when A leaves monitor, then B runs.
- **<u>Issue:</u> What happens while B is waiting?**
  - can the condition that caused A to generate the signal be changed before B runs?
- **In MESA semantics a signal is more like a hint**
  - Requires B to recheck the condition on which it waited to see if it can proceed or must wait some more

Code for the "deposit" entry routine

```
monitor BoundedBuffer
  var buffer: array[n] of char
     nextIn, nextOut: int = 0
     cntFull: int = 0
     notEmpty: Condition
     notFull: Condition

  entry deposit(c: char)
     if cntFull == N
       notFull.Wait()
     endIf
     buffer[nextIn] = c
     nextIn = (nextIn+1) mod N
     cntFull = cntFull + 1
     notEmpty.Signal()
   endEntry

  entry remove()
     ...

endMonitor
```

Hoare Semantics

Code for the "deposit" entry routine

```
monitor BoundedBuffer
  var buffer: array[n] of char
     nextIn, nextOut: int = 0
     cntFull: int = 0
     notEmpty: Condition
     notFull: Condition

  entry deposit(c: char)
     while cntFull == N
       notFull.Wait()
     endWhile
     buffer[nextIn] = c
     nextIn = (nextIn+1) mod N
     cntFull = cntFull + 1
     notEmpty.Signal()
   endEntry

  entry remove()
     ...

endMonitor
```

MESA Semantics

Code for the "remove" entry routine

```
monitor BoundedBuffer
  var buffer: array[n] of char
     nextIn, nextOut: int = 0
     cntFull: int = 0
     notEmpty: Condition
     notFull: Condition

  entry deposit(c: char)
     ...

  entry remove()
     if cntFull == 0
       notEmpty.Wait()
     endIf
     c = buffer[nextOut]
     nextOut = (nextOut+1) mod N
     cntFull = cntFull - 1
     notFull.Signal()
   endEntry

endMonitor
```

Hoare Semantics

Code for the "remove" entry routine

```
monitor BoundedBuffer
  var buffer: array[n] of char
     nextIn, nextOut: int = 0
     cntFull: int = 0
     notEmpty: Condition
     notFull: Condition

  entry deposit(c: char)
     ...

  entry remove()
     while cntFull == 0
       notEmpty.Wait()
     endWhile
     c = buffer[nextOut]
     nextOut = (nextOut+1) mod N
     cntFull = cntFull - 1
     notFull.Signal()
   endEntry

endMonitor
```

MESA Semantics

“Hoare Semantics”

What happens when a Signal is performed?

The signaling thread (A) is suspended.

The signaled thread (B) wakes up and runs immediately.

B can assume the condition is now true/satisfied

From the original Hoare Paper:

“No other thread can intervene [and enter the monitor] between the signal and the continuation of exactly one waiting thread.”

“If more than one thread is waiting on a condition, we postulate that the signal operation will reactivate the longest waiting thread. This gives a simple neutral queuing discipline which ensures that every waiting thread will eventually get its turn.”

Implementing Hoare Semantics

- **Thread A holds the monitor lock**
- **Thread A signals a condition that thread B was waiting on**
- **Thread B is moved back to the ready queue?**
  - B should run immediately
  - Thread A must be suspended...
  - the monitor lock must be passed from A to B
- **When B finishes it releases the monitor lock**
- **Thread A must re-acquire the lock**
  - A is blocked, waiting to re-aquire the lock

Implementing Hoare Semantics

- **Problem:**
  - Possession of the monitor lock must be passed directly from A to B and then eventually back to A

Implementing Hoare Semantics

- **Implementation Ideas:**
  - Consider a signaled thread like B to be "urgent" after A releases the monitor lock
    - **Thread C trying to gain initial entry to the monitor is not "urgent"**
  - Consider two wait lists associated with each *MonitorLock (so now this is not exactly a mutex)*
    - **UrgentlyWaitingThreads**
    - **NonurgentlyWaitingThreads**
  - Want to wake up urgent threads first, if any
  - Alternatively, B could be added to the front of the monitor lock queue

Implementing Hoare Semantics

- **Recommendation for Project 4 implementation:**
  - Do not modify the mutex methods provided, because future code will use them
  - Create new classes:
    - **MonitorLock -- similar to Mutex**
    - **HoareCondition -- similar to Condition**

Brinch-Hansen Semantics

- **Hoare Semantics**
  - On signal, allow signaled process to run
  - Upon its exit from the monitor, signaling process continues.

- **Brinch-Hansen Semantics**
  - Signaler must immediately exit following any invocation of signal
  - Restricts the kind of solutions that can be written
  - … but monitor implementation is easier

Review of a Practical Concurrent Programming Issue – Reentrant Functions

Reentrant code

- **A function/method is said to be reentrant if...**

  A function that has been invoked may be invoked again before the first invocation has returned, and will still work correctly

- **In the context of concurrent programming...**

  A reentrant function can be executed simultaneously by more than one thread, with no ill effects

Reentrant Code

- Consider this function...

```
var count: int = 0
function GetUnique () returns int
  count = count + 1
  return count
endFunction
```

- What if it is executed by different threads concurrently?

Reentrant Code

- Consider this function...

```
var count: int = 0
function GetUnique () returns int
  count = count + 1
  return count
endFunction
```

- What if it is executed by different threads concurrently?
    - The results may be incorrect!
    - This routine is not reentrant!

When is code reentrant?

- **Some variables are**
  - "local" -- to the function/method/routine
  - "global" -- sometimes called "static"
- **Access to local variables?**
  - A new stack frame is created for each invocation
  - Each thread has its own stack
- **What about access to global variables?**
  - Must use synchronization!

Does this work?

```
var count: int = 0
    myLock: Mutex

function GetUnique () returns int
  myLock.Lock()
  count = count + 1
  myLock.Unlock()
  return count
endFunction
```

What about this?

```
var count: int = 0
    myLock: Mutex

function GetUnique () returns int
  myLock.Lock()
  count = count + 1
  return count
  myLock.Unlock()
endFunction
```

Making this function reentrant

```
var count: int = 0
    myLock: Mutex

function GetUnique () returns int
  var i: int
  myLock.Lock()
  count = count + 1
  i = count
  myLock.Unlock()
  return i
endFunction
```

Message Passing

Message Passing

- **Interprocess Communication**
  - via shared memory
  - across machine boundaries

- **Message passing can be used for synchronization or general communication**

- **Processes use send and receive primitives**
  - receive can block (like waiting on a Semaphore)
  - send unblocks a process blocked on receive (just as a signal unblocks a waiting process)

Producer-consumer with message passing

- **The basic idea:**
  - After producing, the producer sends the data to consumer in a message
  - The system buffers messages
    - **The producer can out-run the consumer**
    - **The messages will be kept in order**
  - But how does the producer avoid overflowing the buffer?
    - **After consuming the data, the consumer sends back an "empty" message**
  - A fixed number of messages (N=100)
  - The messages circulate back and forth.

Producer-consumer with message passing

```
const N = 100                -- Size of message buffer
var em: char
for i = 1 to N               -- Get things started by
  Send (producer, &em)       --    sending N empty messages
endFor
```

```
thread consumer
  var c, em: char
  while true
    Receive(producer, &c)      -- Wait for a char
    Send(producer, &em)        -- Send empty message back
    // Consume char...
  endWhile
end
```

Producer-consumer with message passing

```
thread producer
  var c, em: char
  while true
    // Produce char c...
    Receive(consumer, &em)    -- Wait for an empty msg
    Send(consumer, &c)        -- Send c to consumer
  endWhile
end
```

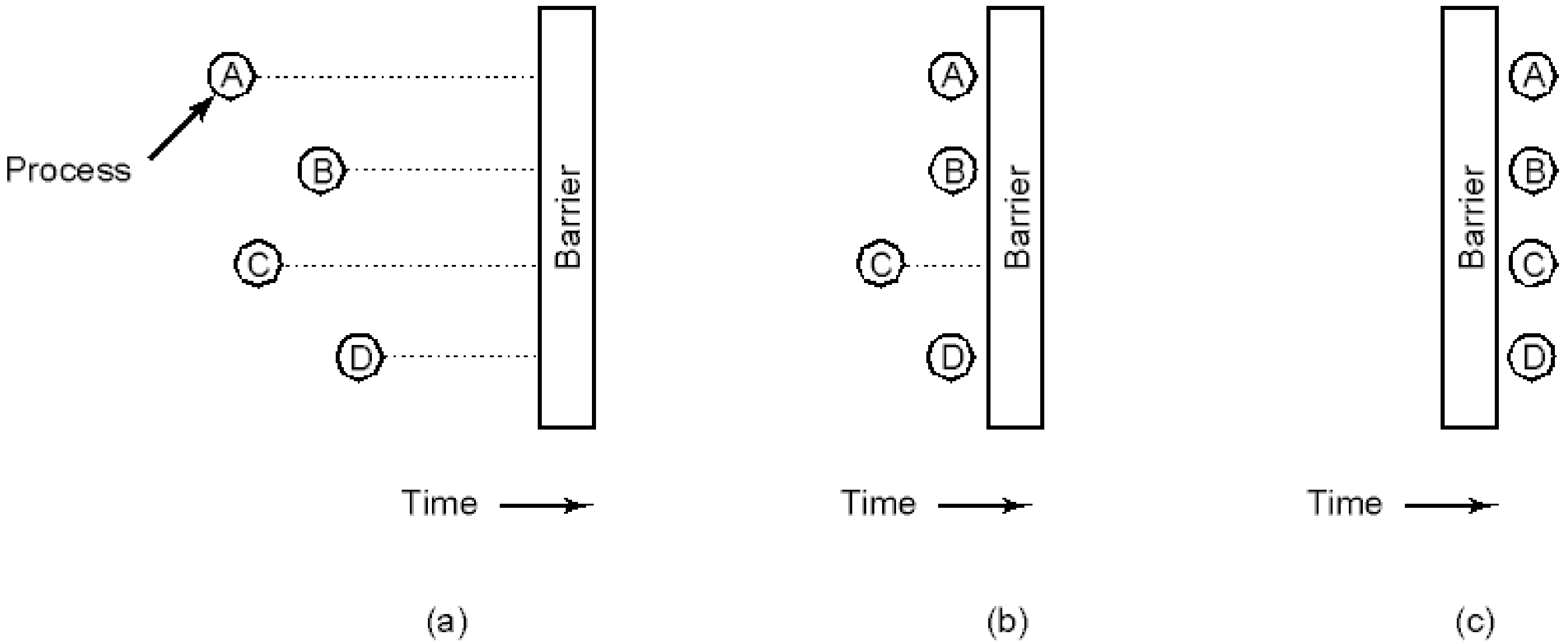
Design choices for message passing

- **Option 1: Mailboxes**
  - System maintains a buffer of sent, but not yet received, messages
  - Must specify the size of the mailbox ahead of time
  - Sender will be blocked if the buffer is full
  - Receiver will be blocked if the buffer is empty

Design choices for message passing

- **Option 2:** **No buffering**
  - If Send happens first, the sending thread blocks
  - If Receiver happens first, the receiving thread blocks
  - Sender and receiver must Rendezvous (ie. meet)
  - Both threads are ready for the transfer
  - The data is copied / transmitted
  - Both threads are then allowed to proceed

Barriers



- Processes approaching a barrier
- All processes but one blocked at barrier
- Last process arrives; all are let through

Quiz

- **What is the difference between a monitor and a semaphore?**
  - Why might you prefer one over the other?
- **How do the wait/signal methods of a condition variable differ from the wait/signal methods of a semaphore?**
- **What is the difference between Hoare and Mesa semantics for condition variables?**
  - What implications does this difference have for code surrounding a wait() call?