CG2271

Real-Time Operating Systems

Lecture 7

Inter-Task Communication

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Learning Objectives

- **By the end of this lecture you will be able to:**
  - Understand what race conditions are, and why they are bad.
  - Understand the various ways to prevent race conditions.
  - Understand how to pass messages between tasks.

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Introduction

- **In the "previous, previous" lecture we looked at how multiple tasks can run on a single CPU.**
- **In the previous lecture, we then looked at how a kernel chooses which task to run next.**
  - We basically assumed that tasks are independent!
- **In real-world applications, there are "dependencies" between tasks.**
  - Task B cannot proceed because it is waiting for Task A's result.
  - Task B and Task A update the same shared variable, which can result in errors.
  - …

Introduction

- **If both Task A and Task B are allowed to run freely, errors will occur.**
  - Task B proceeds before Task A completes, resulting in B using stale results.
  - Task A and B update a variable at the same time, causing one task to over-write the results of the other task.
  - Etc.
- **Some form of coordination is therefore required!**
- **This lecture comes from Modern Operating Systems.**
  - MOS uses the term "process" instead of task.
  - To be consistent with the book, we will therefore also say "process" instead of task.
    - ✓**Just remember that they mean the same thing!!**

Inter-Task Communications

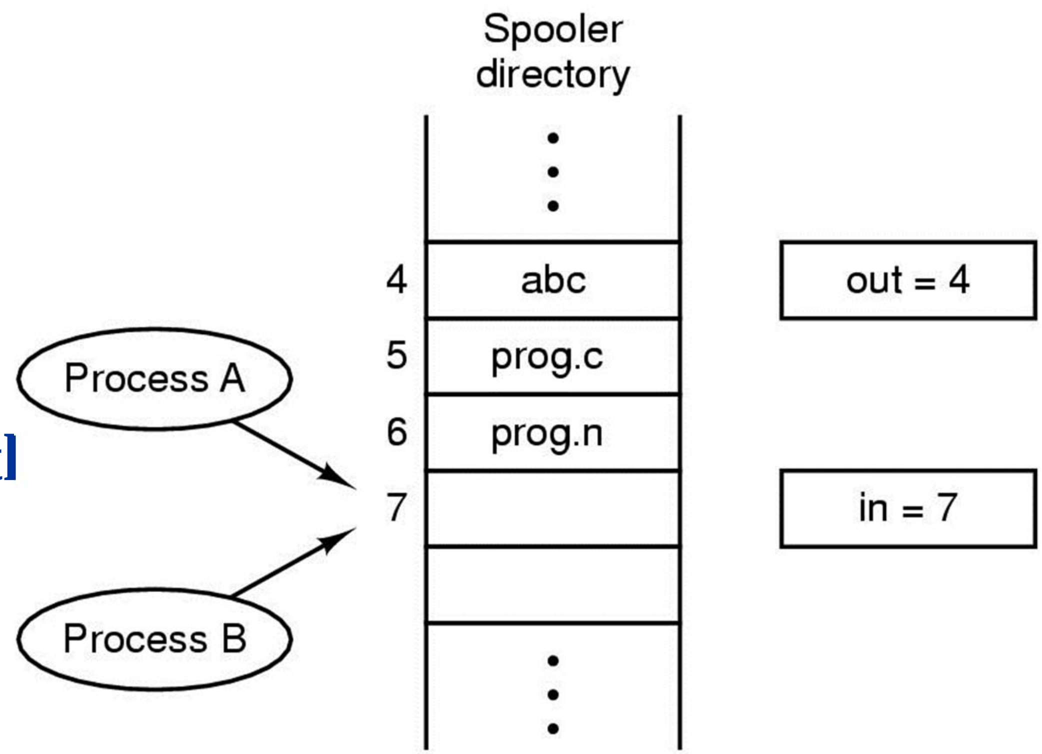
RACE CONDITIONS AND CRITICAL SECTIONS

Race Conditions

- **Race conditions occur when two or more processes attempt to access shared storage.**
  - This causes the final outcome to depend on who runs first.
  - “Shared storage” can mean:
    - ✓**Global variables.**
    - ✓**Memory locations.**
    - ✓**Hardware registers.**
      - *This refers to configuration registers rather than CPU registers.*
    - ✓**Files.**
  - To understand race conditions, we will consider the example of a queue in a print spooler.

Race Conditions

- **A process that wants to print enters the name of the file into a print directory.**
- **A print daemon (printd) periodically checks the directory, prints out the next file and removes its entry.**
- **Two variables keep track of tl queue:**
  - IN: Next available slot.
  - OUT: Next file for printing.



Race Conditions

- **The following can happen:**
  - Process A reads IN as 7 and stores it in a local variable *next*.
  - The OS pre-empts A and starts B.
  - B reads IN as 7 and stores it in a local variable *next*.
  - B inserts its file into slot 7 and updates IN to 8.
  - B is pre-empted and A restarts.
  - A still thinks slot 7 is available and inserts its file there, overwriting B's file, then updates IN to 8.
- **The daemon is unaware of the mistake, and B never gets a printout. ☹**

Critical Sections

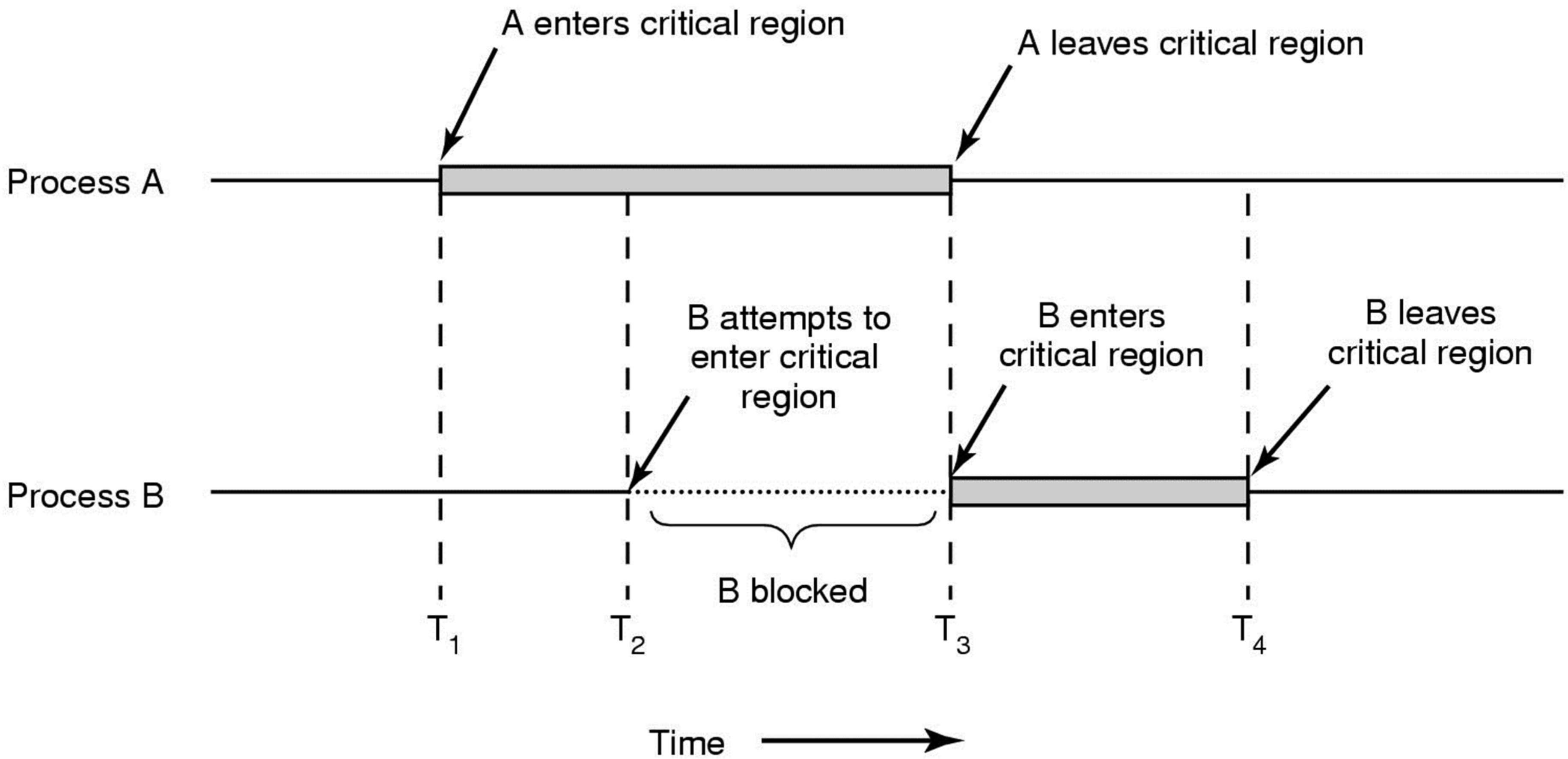
- **To prevent race conditions, we must prevent two processes from reading/writing shared resources at the same time.**
- **This is known as a "mutual exclusion", shortened to "mutex".**
- **Conceptually, a RUNNING process is always in one of two possible states:**
  - It is performing local computation. This does not involve global storage, hence to race condition is possible.
  - It is reading/updating global variables. This can lead to race conditions.
- **When a RUNNING process is in the second state, it is within its "critical section".**

Critical Sections

- **To prevent race conditions, 4 rules must be followed:**
  - No two processes can simultaneously be in their critical section.
  - No assumptions may be made about speeds or # of CPUs.
    - ✓ **Note: We can relax this assumption for *most* embedded systems since they have single CPUs.**
    - ✓ **May apply to systems using multicore microcontrollers.**
  - No process outside of its critical section can block other processes.
  - No process should wait forever to enter its critical section.

Critical Sections

- **In an ideal state, this is how mutual exclusion works:**



Inter-Task Communications

IMPLEMENTING MUTUAL EXCLUSION

Implementing Mutual Exclusion

- **There are several ways of implementing mutexes, each with their own + and – points:**
  - Disabling interrupts.
  - Lock variables.
  - Strict alternation.
  - Perterson's Solution.
  - Test and set lock.
  - Sleep/Wakeup

Implementing Mutual Exclusion Disabling Interrupts

- **Disabling Interrupts.**
  - This works because:
    - ✓**Time-slicing depends on a timer interrupt. If this is disable, the scheduler is never activated to switch to another process.**
    - ✓**Similarly, processes that are blocked pending an event (e.g. arrival of data from the network), depend on an interrupt to tell the scheduler that the event has taken place.**
  - Therefore disabling interrupts will prevent other processes from starting up and entering their critical sections.

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Implementing Mutual Exclusion Disabling Interrupts

- **Disabling Interrupts.**
  - There are several problems with this approach:
    - ✓**Carelessly disabling interrupts can cause the entire system to grind to a halt.**
    - ✓**This only works on single-processor, single core systems. Violates Rule 2.**

Implementing Mutual Exclusion
Lock Variables

- **Using Lock Variables.**
  - A single global variable “lock” is initially 1.
  - Process A reads this variable and sets it to 0, and enters its critical section.
  - Process B reads “lock” and sees it’s a 0. It doesn’t enter its critical section and waits until “lock” is 1.
  - Process A finishes and sets “lock” to 1, allowing B to enter.

Implementing Mutual Exclusion
Lock Variables

- **This approach obviously doesn't work!!**
  - Process A reads in "lock" and sees a "1". It gets pre-empted and Process B runs.
  - Process B reads in "lock", sees a "1", sets it to 0 and enters its critical section.
  - Before B leaves, A is re-started, and enters the critical section.
- **Now >1 process is in the critical section!**
- **PROBLEM: There's a race condition on "lock" itself!**

Implementing Mutual Exclusion
Strict Alternation

```
while (TRUE) {
    while (turn != 0)       /* loop */ ;
    critical_region( );
    turn = 1;
    noncritical_region( );
}
```

(a)

```
while (TRUE) {
    while (turn != 1)       /* loop */ ;
    critical_region( );
    turn = 0;
    noncritical_region( );
}
```

(b)

- **A "turn" variable keeps track of whose turn it is to enter the critical section.**
- **If it is currently "0", then A will enter and B will continuously test until it becomes "1".**
- **Once A finishes its critical section, it flips "turn" to 1 allowing B to enter the critical region. B flips it back to 0 when done.**

Implementing Mutual Exclusion Strict Alternation

- **Problems (assume “turn”=0):**
  - Since “turn” is 0, B just loops infinitely waiting for “turn” to be 1.
    - ✓**This is called “busy-waiting” and burns valuable CPU time for no reason.**
  - If “A” is spending a lot of time in its non-critical section, it will not reach the part of the loop where it flips “turn” to 1.
  - Result is that B cannot enter it’s critical section even though no one is there!
- **Violates Rule #3.**

Implementing Mutual Exclusion Peterson's Solution

```
#define FALSE  0
#define TRUE   1
#define N      2                      /* number of processes */

int turn;                             /* whose turn is it? */
int interested[N];                    /* all values initially 0 (FALSE) */

void enter_region(int process);       /* process is 0 or 1 */
{
      int other;                      /* number of the other process */

      other = 1 – process;            /* the opposite of process */
      interested[process] = TRUE;     /* show that you are interested */
      turn = process;                 /* set flag */
      while (turn == process && interested[other] == TRUE) /* null statement */ ;
}

void leave_region(int process)        /* process: who is leaving */
{
      interested[process] = FALSE;    /* indicate departure from critical region */
}
```

Implementing Mutual Exclusion Peterson's Solution

- **Suppose Process A (i.e. process 0) wants to enter it's critical section.**
  - It calls enter_region.
    - ✓ **"other" is set to 1, "turn" is set to 0.**
    - ✓ **interest[0] is set to 1.**
    - ✓ **Since "interest[other]=interest[1]=0", the while loop exits immediately and A enters the critical section.**
  - If Process B (process 1) wants to enter and calls "enter region":
    - ✓ **"other is set to 0, "turn" is set to 1, interest[1] is set to 1.**
    - ✓ **It checks "interest[other]=interest[0]=1", it loops until interest[0] is set to 0.**
  - When process A ends, it calls leave_region which sets interest[0] to 0 and allows Process B to exit the while loop.

Test and Set Lock

- **Many microprocessors have an instruction that looks like this:**
  - TSL reg, lock ; lock is a variable in memory
- **How this works:**
  - CPU locks the address and data buses, and reads “lock” from memory.
    - ✓**The locked address and data buses will block accesses from all other CPUs.**
  - The current value is written into register “reg”.
  - A “1” (or sometimes “0”) value is written to “lock”.
  - CPU unlocks the address and data buses.
- **The TSL is “atomic”.**
  - This means that NOTHING can interrupt execution of this instruction.
  - This is guaranteed in hardware.

Test and Set Lock

- **The TSL instruction is used as follows:**

```
enter_region:
    TSL REGISTER,LOCK          | copy lock to register and set lock to 1
    CMP REGISTER,#0            | was lock zero?
    JNE enter_region           | if it was non zero, lock was set, so loop
    RET | return to caller; critical region entered


leave_region:
    MOVE LOCK,#0               | store a 0 in lock
    RET | return to caller
```

Test and Set Lock

- **An alternative is the XCHG instruction, used on Intel machines.**
  - Swaps contents of “lock” and “reg” instead of just writing “1” to lock.

```
enter region:
        MOVE REGISTER, #1          ; Set REGISTER to 1
        XCHG REGISTER, LOCK        ; Exchange with Lock
        CMP REGISTER, #0           ; Was Lock 0?
        JNE enter_region           ; No, go back and try again.
        RET                        ; Yes, enter critical region.

leave_region:
        MOVE LOCK, #0              ; Clear the lock
        RET                        ; And exit
```

Deadlock

- **Busy-wait approaches like Peterson and TSL/XCHG have a problem called "deadlock".**
- **Consider two processes H and L, and a scheduler rule that says that H is always run when it is READY. Suppose L is currently in the critical region.**
  - H becomes ready, and L is pre-empted.
  - H tries to obtain a lock, but cannot because L is in the critical region.
  - H loops forever, and CPU control never gets handed to L.
  - As a result L never releases the lock.
- **Note: The book calls this a "priority inversion", which is incorrect.**

Sleep/Wake

- **One solution to this problem is through the use of "Sleep/Wake" functions.**
  - When a process finds that a lock has been set (i.e. another process in the critical section), it calls "sleep" and is put into the blocked state.
  - When the other process exits the critical section and clears the lock, it can call "wake" which moves the blocked process into the READY queue for eventual execution.
- **While this sounds like an ideal solution, it can create a problem called the "producer-consumer problem".**

Inter-Task Communications

THE PRODUCER/CONSUMER PROBLEM

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The Producer/Consumer problem

```
#define N 100                               /* number of slots in the buffer */
int count = 0;                              /* number of items in the buffer */

void producer(void)
{
      int item;

      while (TRUE) {                        /* repeat forever */
            item = produce_item( );         /* generate next item */
            if (count == N) sleep( );       /* if buffer is full, go to sleep */
            insert_item(item);              /* put item in buffer */
            count = count + 1;              /* increment count of items in buffer */
            if (count == 1) wakeup(consumer);  /* was buffer empty? */
      }
}


void consumer(void)
{
      int item;

      while (TRUE) {                        /* repeat forever */
            if (count == 0) sleep( );       /* if buffer is empty, got to sleep */
            item = remove_item( );          /* take item out of buffer */
            count = count – 1;              /* decrement count of items in buffer */
            if (count == N – 1) wakeup(producer);  /* was buffer full? */
            consume_item(item);             /* print item */
      }
}
```

The Producer/Consumer problem

- **Producer and consumer share a fixed-size buffer.**
  - A global variable "count" keeps track of the number of items.
    - ✓ **If count==N (FULL), producer sleeps, if count==0 (EMPTY) consumer sleeps.**
  - After reading from the buffer, if count==N-1:
    - ✓ **Consumer reasons that the buffer was earlier full and wakes the producer.**
  - After writing to the buffer, if count==1
    - ✓ **Producer reasons that the buffer was earlier empty and wakes the consumer.**

The Producer/Consumer problem

- **Deadlock occurs when:**
  - Consumer checks “count” and finds it is 0.
  - Consumer gets pre-empted and producer starts up.
  - Producer adds an item, increments count to “1”, then sends a WAKE to the consumer.
    - ✓**Since consumer is not technically sleeping yet, the WAKE is lost.**
  - Consumer starts up, and since count is 0, goes to SLEEP.
  - Producer starts up, fills buffer until it is full and SLEEPs.
- **Since consumer is also SLEEPing, no one wakes the producer. Deadlock.**

Inter-Task Communications

SEMAPHORES

Semaphores

- **A semaphore is a special lock variable that counts the number of wake-ups saved for future use.**
  - A value of "0" indicates that no wake-ups have been saved.
- **Two ATOMIC operations on semaphores:**
  - DOWN, PEND or P:
    - ✓**If the semaphore has a value of >0, it is decremented and the DOWN operation returns.**
    - ✓**If the semaphore is 0, the DOWN operation blocks.**
  - UP, POST or V:
    - ✓**If there are any processes blocking on a DOWN, one is selected and woken up.**
    - ✓**Otherwise UP increments the semaphore and returns.**

Using Semaphores in the Producer/Consumer Problem

```
#define N 100                          /* number of slots in the buffer */
typedef int semaphore;                 /* semaphores are a special kind of int */
semaphore mutex = 1;                   /* controls access to critical region */
semaphore empty = N;                   /* counts empty buffer slots */
semaphore full = 0;                    /* counts full buffer slots */

void producer(void)
{
     int item;

     while (TRUE) {                    /* TRUE is the constant 1 */
          item = produce_item( );      /* generate something to put in buffer */
          down(&empty);                /* decrement empty count */
          down(&mutex);                /* enter critical region */
          insert_item(item);           /* put new item in buffer */
          up(&mutex);                  /* leave critical region */
          up(&full);                   /* increment count of full slots */
     }
}


void consumer(void)
{
     int item;

     while (TRUE) {                    /* infinite loop */
          down(&full);                 /* decrement full count */
          down(&mutex);                /* enter critical region */
          item = remove_item( );       /* take item from buffer */
          up(&mutex);                  /* leave critical region */
          up(&empty);                  /* increment count of empty slots */
          consume_item(item);          /* do something with the item */
     }
}
```

- EMPTY - # of empty slots.
- FULL - # of full slots.
- MUTEX – Prevents simultaneous access to the buffer.

Mutual Exclusion with Semaphores

- **When a semaphore's counting ability is not needed, we can use a simplified version called a "mutex".**
  - 1 = Unlocked.
  - 0 = Locked.
- **Two processes can then attempt do DOWN the semaphore.**
  - Only one will succeed. The other will block.
  - When the successful process exits the critical section, it does an UP, waking the other process up.

Mutual Exclusion with Semaphores

Process A

```
sema=1
…
non_critical_section()
DOWN(sema)
critical_section()
UP(sema)
…
```

Process B

```
non_critical_section()
DOWN(sema)
critical_section()
UP(sema)
…
```

Mutual Exclusion with TSL/XCHG

- **We can also implement mutexes with TSL or XCHG.**
  - 0 = Unlocked, 1 = Locked.

```
mutex_lock:
      TSL REGISTER,MUTEX           | copy mutex to register and set mutex to 1
      CMP REGISTER,#0              | was mutex zero?
      JZE ok                       | if it was zero, mutex was unlocked, so return
      CALL thread_yield            | mutex is busy; schedule another thread
      JMP mutex_lock               | try again later
ok:   RET | return to caller; critical region entered


mutex_unlock:
      MOVE MUTEX,#0                | store a 0 in mutex
      RET | return to caller
```

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Problems with Semaphores

Deadlock

- **Our producer/consumer solution has a problem:**
  - If we swapped the semaphores for empty/full with the mutex semaphore, we have a potential deadlock:

```
#define N 100                           /* number of slots in the buffer */
typedef int semaphore;                  /* semaphores are a special kind of int */
semaphore mutex = 1;                    /* controls access to critical region */
semaphore empty = N;                    /* counts empty buffer slots */
semaphore full = 0;                     /* counts full buffer slots */

void producer(void)
{
     int item;

     while (TRUE) {                     /* TRUE is the constant 1 */
          item = produce_item( );       /* generate something to put in buffer */
          down(&mutex);                 /* decrement empty count */
          down(&empty);                 /* enter critical region */
          insert_item(item);            /* put new item in buffer */
          up(&mutex);                   /* leave critical region */
          up(&full);                    /* increment count of full slots */
     }
}

void consumer(void)
{
     int item;

     while (TRUE) {                     /* infinite loop */
          down(&mutex);                 /* decrement full count */
          down(&full);                  /* enter critical region */
          item = remove_item( );        /* take item from buffer */
          up(&mutex);                   /* leave critical region */
          up(&empty);                   /* increment count of empty slots */
          consume_item(item);           /* do something with the item */
     }
}
```

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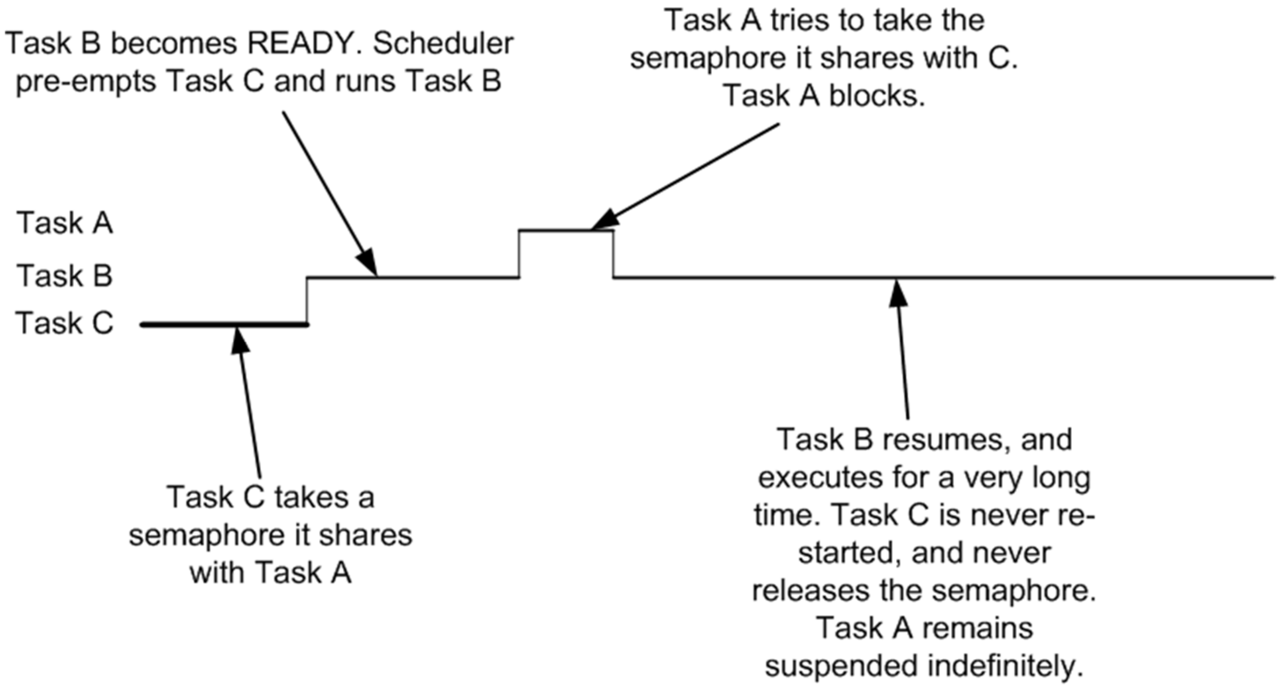
Problems with Semaphores Deadlock

- **This can happen:**
  - Producer successfully DOWNs the mutex.
  - Producer DOWNs “empty”. However the queue is full so this blocks.
  - Consumer DOWNs mutex and blocks.
    - ✓ **Consumer now never reaches the UP for “empty” and therefore cannot unblock the producer.**
    - ✓ **The producer in turn never reaches the UP for mutex and cannot unblock the consumer.**
    - ✓ **Deadlock!**

Problems with Semaphores Priority Inversion

- **In the diagram on the following page, priority(Task C) < priority(Task B) < priority(Task A).**



- **Task B effectively blocks out Task A, although Task A has higher priority!**

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MONITORS

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Monitors

- **A monitor is similar to a class or abstract-data type in C++ or JAVA:**
  - Collection of procedures, variables and data structures grouped together in a package.
    - ✓**Access to variables and data possible only through methods defined in the monitor.**
  - However, only one process can be active in a monitor at any point in time.
    - ✓**I.e. if any other process tries to call a method within the monitor, it will block until the other process has exited the monitor.**

Monitors

- **Implementation:**
  - When a process calls a monitor method, the method first checks to see if any other process is already using it.
  - If so, the calling process blocks until the other process has exited the monitor.
    - ✓**This can be achieved using mutexes or binary semaphores.**
    - ✓**The mutex/semaphore operations are inserted by the compiler itself rather than by the user, reducing the likelihood of errors.**

Monitors and Condition Variables

- **Monitors achieve mutual exclusion, but we also need other mechanisms for coordination.**
  - E.g. in our producer/consumer problem, mutual exclusion alone is not enough to prevent the producer from proceeding when the buffer is full.
- **We introduce “condition variables”.**
  - One process WAITs on a condition variable and blocks, until..
  - Another process SIGNALs on the same condition variable, unblocking the WAITing process.

Monitors and Condition Variables

- **Implementing the Producer/Consumer problem with semaphores and condition variables:**
  - When the buffer is full (count==N), producer will WAIT on a full condition.
  - When buffer is empty (count==0), consumer will WAIT on empty.

```
monitor ProducerConsumer
    condition full, empty;
    integer count;
    procedure insert(item: integer);
    begin
        if count = N then wait(full);
        insert_item(item);
        count := count + 1;
        if count = 1 then signal(empty)
    end;
    function remove: integer;
    begin
        if count = 0 then wait(empty);
        remove = remove_item;
        count := count − 1;
        if count = N − 1 then signal(full)
    end;
    count := 0;
end monitor;

procedure producer;
begin
    while true do
    begin
        item = produce_item;
        ProducerConsumer.insert(item)
    end
end;
procedure consumer;
begin
    while true do
    begin
        item = ProducerConsumer.remove;
        consume_item(item)
    end
end;
```

Monitors and Condition Variables

- **When a process encounters a WAIT, it is blocked and another process is allowed to enter the monitor.**
- **Problem:**
  - When there's a SIGNAL, the sleeping process is woken up.
  - We will potentially now have two processes in the monitor at the same time:
    - ✓ **The process doing the SIGNAL (the signaler).**
    - ✓ **The process that just woke up because of the SIGNAL (the signaled).**

Monitors and Condition Variables

- **We have 3 ways to resolve this:**
  - We require that the signaler exits immediately after calling SIGNAL.
  - We suspend the signaler immediately and resume the signaled process.
  - We suspend the signaled process until the signaler exits, and resume the signaled process only after that.

Monitors and Condition Variables

- **A condition variable is different from a semaphore.**
  - Semaphore:
    - ✓**If Process A UPs a semaphore with no pending DOWN, the UP is saved.**
    - ✓**The next DOWN operation will not block because it will match immediately with a preceding UP.**
  - Condition variable:
    - ✓**If Process A SIGNALs a condition variable with no pending WAIT, the SIGNAL is simply lost.**
    - ✓**This is similar to the SLEEP/WAKE problem earlier on.**

Monitors and Condition Variables

- **This code looks suspiciously like our original producer/consumer problem on Page 23!**
  - Same issues too:
    - ✓**Page 23:**

      Consumer sees count==0, and intends to SLEEP but gets pre-empted.

      Producer sends a WAKE but the WAKE is lost.

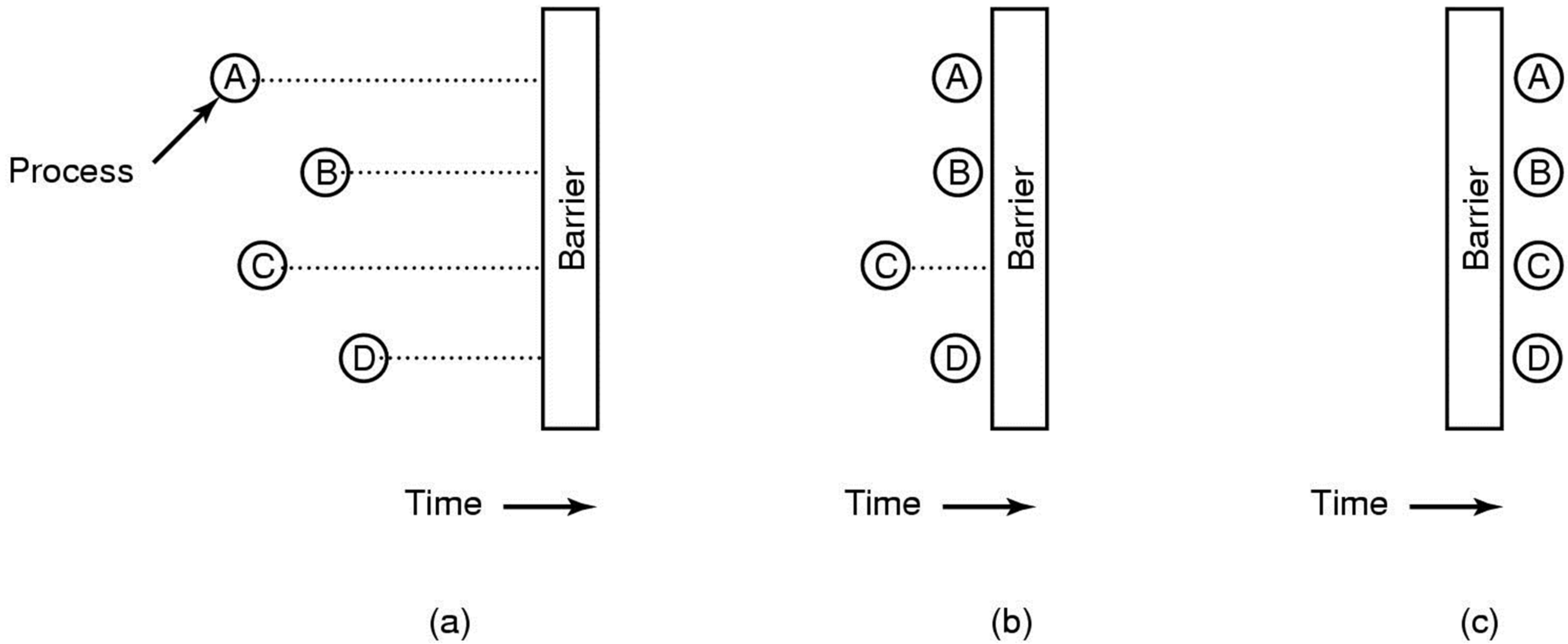
      In this case, if the consumer gets pre-empted before a WAIT, the corresponding SIGNAL from the producer is also lost!
    - ✓**However we see that in this case, the mutual exclusion from the monitor prevents the SIGNAL from being lost! (WHY?)**

Inter-Task Communications

BARRIERS

Barriers

- **A "barrier" is a special form of synchronization mechanism that works with groups of processes rather than single processes.**



Barriers

- **The idea of a barrier is that all processes must reach the barrier (signifying the end of one phase of computation) before any of them are allowed to proceed.**
    - Process D reaches the end of the current phase and calls a BARRIER primitive in the OS. It gets blocked.
    - Similarly processes A and B reach the end of the current phase, calls the same BARRIER primitive and is blocked.
    - Finally process C reaches the end of its computation, calls the BARRIER primitive, causing all processes to be unblocked at the same time.

Barriers

- **Example barrier application.**
  - Computing fluid motion across a surface represented by a 1,000,000 x 1,000,000 matrix.
    - ✓**The complete matrix for iteration *N* must be available before computing for iteration *N+1*.**
    - ✓**1,000 individual processes each computing a part of the entire matrix.**
    - ✓**We must wait for all 1,000 processes to complete finding the entire matrix before we can start on the next iteration.**
  - A barrier would be very useful in achieving this.

Inter-Task Communications

COMMUNICATION MECHANISMS

Other Communication Mechanisms

- **The mechanisms we've looked at are largely for coordination.**
  - Locks, semaphores, monitors, etc.
  - Any communication takes place through global variables.
- **We will now look at several mechanisms that combine coordination with communication.**
  - Can help eliminate global variables and reduce errors.
- **Mechanisms we will look at:**
  - Queues
  - Mailboxes
  - Pipes

Inter-Task Communications

QUEUES

Queues

- **Queues have four operations:**
  - q = initq(ptr, size): Initializes the queue of size “size” at memory location “ptr”. Returns the queue identifier “q”.
  - enq(q, data): Adds a new item “data” to the tail of the queue “q”.
    - ✓**Returns an error message when the queue is full.**

Queues

- data = deq(q, timeout): Reads and removes an item from the head of the queue and returns it.
  - ✓**Blocks if the queue is empty, up to a specific time specified by “timeout”.**
  - ✓**If timeout is 0, deq blocks forever until there is a message in the queue.**
- destroy(q): Destroys a queue. A queue, once destroyed, cannot be used unless you call initq again.

Queues

- **The RTOS guarantees the correctness of the queue operations.**
  - If a task gets pre-empted in the middle of an enq or deq operation, the RTOS ensures that the operation is completed correct.
  - E.g. if the second task calls enq to the same queue, the RTOS can block it until the first task completes enq properly.

Example

- **Consider a case with two tasks Task1 and Task2.**
  - Both are high priority, with urgent things to attend to.
- **If they encounter an error, they need to report this error across a network.**

Example

- **Writing to a network is typically time consuming:**
  - Hundreds of instructions to transfer data to buffers, wait for acknowledgement etc.
  - Latencies in waiting to access the network medium.
- **Makes sense to partition this into another lower priority task.**

Example

- **Task1 and Task2 must therefore share data with this error reporting task *ErrorsTask*.**
- **For our example we will assume that the queue is properly initialized.**

Queue Example

- **Task Codes**

```
void Task1(void)
{
  ……
  if(!!problem arises)
      vLogError(ERROR_TYPE_X);
  ……
}

Void Task2(void)
{
  ……
  if(!!problem arises)
      vLogError(ERROR_TYPE_Y);
  ……
}
```

Queue Example

```
void vLogError(int iErrorType)
{
  enq(q, iErrorType);
}
static int cErrors;
void ErrorsTask(int iErrorType)
{
  int iErrorType = deq(q, 0);
  ++cErrors;
  !! send cErrors and iErrorType across network.
}
```

Inter-Task Communications

MAILBOXES

Mailboxes

- **A mailbox is like a queue, except:**
  - The number of mailboxes within a system is typically fixed.
    - ✓**This number is initialized when your application first starts.**
    - ✓**Not possible to add more mailboxes.**
    - ✓**Unlike queues, which you can create as and when you need them.**

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Mailboxes

- A mailbox message is also often prioritized.
  - ✓**In a queue, the data is read in the order that it is written.**
  - ✓**Higher priority messages in a mailbox are read ahead of lower priority messages, regardless of the order of writing.**

Mailbox Operations

- **Several operations are defined on mailboxes.**
  - initmbox(num): Initializes “num” mailboxes in the system. Can only be done once.
  - sendmsg(mbID, message, priority): Uses mailbox “mbID” to send a message at the given priority.
  - rcvmsg(mbID): Gets the highest priority message from mbID. Blocks if there are no messages.
  - chkmsg(mbID): Similar to rcvmsg, but returns NULL if the mailbox is empty instead of blocking.

Inter-Task Communications

PIPES

Pipes

- **A pipe is like a queue:**
  - Not prioritized. Messages are read in the order that they are written.
  - Can be created and deleted as and when required.
- **However a pipe is generally byte-oriented.**
  - A queue, for example, reads/writes an entire integer, which may consist of between 2 and 8 bytes.
  - A pipe reads/writes in units of 1 byte.
- **This can give more flexible message passing.**

Pipes

- **Pipe Operations:**
  - Standard C *fread* and *fwrite* functions.
- **Pipes are usually ready-supported by desktop operating systems.**
  - Using pipes allows your programs to be ported to desktop OSes that are adapted for RTOS use.
    - ✓**E.g. BlueCat, a Linux derivative.**

Inter-Task Communications

SELECTING MECHANISMS

Choosing Between Message Passing Methods

- **Each method has its advantages and drawbacks:**
  - Semaphores:

    GOOD: Fast, lightweight.

    BAD: Can be difficult to use correctly.

    For example, you may find yourself having to set up multiple semaphores: One to coordinate between processes, another to protect data updates.

    A semaphore that is taken too late or released too early can be worse than not having a semaphore at all.

Choosing Between Message Passing Methods

- Queues:
  - **GOOD: Simple to use.**
    - *Initialize, enqueue data, dequeue data.*
    - *All task coordination is achieved through the queue.*
    - *RTOS guarantees queue data integrity.*
  - **BAD: No message priorities, heavier than semaphores.**
    - *Need to manage queue "head" and "tail" pointers.*
    - *Need to guarantee correctness of enq and deq operations.*

Choosing Between Message Passing Methods

- Mailboxes:

  GOOD: Intuitively appealing.

  Each task has its own mailbox to pass it messages.

  GOOD: Prioritized messaging.

  Tasks can be read by priority instead of FIFO.

  BAD: Even heavier than queues.

  Extra code to ensure that maxilbox messages are sorted by priority.

  Can be very expensive for large mailboxes.

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Choosing Between Message Passing Methods

- Pipes
  - ✓**GOOD: Byte level mechanisms. Very flexible for passing data.**
  - ✓**GOOD: Supported by almost all desktop OSes**

    Allows you to port your software to such OSes that have been adapted to RTOS.
  - ✓**BAD: Byte-level operations are often more error prone.**

Choosing Between Message Passing Methods

- Pipes
  - ✓**BAD: Byte-level operations are slow.**

    CPUs transfer in fixed numbers of bytes called the "word size".

    Byte level operations would mean chopping up and joining words.
  - ✓**BAD: No priorities.**

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Choosing Between Message Passing Methods

- **The RTOS manuals will list the sizes and expected execution times for each mechanism.**
- **It is critical that you choose the best mechanism for your application.**
  - Do you need maintainability, priority, execution speed or small footprint?
- **RTOSs sometimes allow you to remove mechanisms that you don't use.**
  - Might think about sticking with just one mechanism.

Inter-Task Communications

POTENTIAL PITFALLS

Potential Pitfalls

- **While queues, mailboxes and pipes simplify data sharing, they also make it easy to insert bugs into your system**
- **For readability, the pitfalls listed talk about queues. Unless otherwise stated, they apply to mailboxes and pipes as well.**

Potential Pitfalls

1. **Reading/Writing to the wrong queue.**
   - RTOSs don't have the ability to restrict a queue to a particular task.
   - If one task writes temperature data to the error messages queue, then the error handling task will get confused.
2. **Wrong Queue Semantics**
   - Task A writes integers to a queue.
   - Task B reads the queue and interprets the data as a pointer to an integer, instead of the integer itself.

Potential Pitfalls

```
OSEVENT *pq;
// Prototype for the enq and deq functions
void enq(OSEVENT *q, void *data);
void *deq(OSEVENT *q);

void taskA(void)
{
    int datum;
    … some processing on datum …
    // Enqueue an integer “datum”, casting it as
    // void * to fit the enq prototype.
    enq(pq, (void *) datum);
}
```

Potential Pitfalls

```
void taskB(void)
{
    int *dataptr;

    dataptr = (int *) deq(pq);
    *dataptr = !! Result of some computation.
}
```

- This code is a disaster because taskB is going to (almost) randomly overwrite memory that is used by other tasks.
    - Remember that there is no memory protection in most RTOS!

Potential Pitfalls

3. Running out of space.
   - This is a disaster because the data being passed is not usually optional.
4. Inadvertently creating unprotected shared variables.
   - This happens when you pass pointers instead of data.
   - If you pass data, the RTOS ensures that the enq and deq operations place and remove the data correctly from the queue.
   - If you pass pointers, the RTOS ensures that the enq and deq operations place and remove the pointers correctly from the queue.
     - BUT: The data the pointers point to are themselves not protected!

Potential Pitfalls

```
OSEVENT *pq;
// Prototype for the enq and deq functions
void enq(OSEVENT *q, void *data);
void *deq(OSEVENT *q);

void vReadTemperaturesTask(void)
{
    static int iTemperatures[2];
    while(1)
    {
      iTemperatures[0] = !! Read in temp1 from hw
      iTemperatures[1] = !! Read in temp2 from hw

      // Add address of iTemperatures to queue
      enq(pq, (void *) iTemperatures);
    }
```

Potential Pitfalls

```
void vMainTask(void)
{
    int *pTemp;

    while(1)
    {
      pTemp = (int *) deq(pq);
      if(pTemp[0] != pTemp[1])
            !! Set of howling alarm
    }
}
```

Potential Pitfalls

i. *vMainTask* will get the address of *iTemperatures* from the queue, assigning it to *pTemp*.

ii. It then reads *pTemp[0]* (which is *iTemperatures[0]* since *pTemp* points to the same *iTemperatures* array).

iii. *vMainTask* gets pre-empted, and *vReadTemperaturesTask* updates *iTemperatures[0]* and *iTemperatures[1]*.

Potential Pitfalls

iv. *vMainTask* resumes, and reads in *pTemp[1]*.

v. The comparison will fail, causing the alarm to be triggered errorneously.

Summary

- **In this lecture we looked at:**
  - What race conditions and critical sections are.
  - Mechanisms to prevent race conditions.
  - Mechanisms that provide both coordination and communication functions.