Tasks and Intertask Communication

Introduction

- Multitasking / Multithreading system
  - Supports multiple tasks

- As we've noted
  - Important job in multitasking system
    - Exchanging data between tasks
    - Synchronizing tasks
    - Sharing resources

- Let's now examine these issues

Interprocess / Interthread Communication

- When threads operating independently
  - Our systems have few if any
    - Conflicts
    - Chances for corruption
    - Contentions
- Real systems
  - The interesting ones
  - Must deal with all such problems
- Resources and inter thread communication
  - Must take place in robust manner

- Interaction may be
  - Direct or indirect
  - Must be synchronized and co-ordinated
    - Want to prevent race conditions
      - Outcome of task or computation
        - Depends upon order in which tasks execute
- Let's begin by looking at shared information
  - Can occur in a variety of ways

Shared Variables

Simplest solution is shared memory environment

Global Variables

- Simplest and fastest of these is
  - Global variables
    - Obvious problems
      - Higher priority process can pre-empt
        - Modify global data

Shared Buffer

- Scheme says two processes share common set of
  - Memory locations
- Producer
  - Puts data into buffer
- Consumer
  - Removes
- Several obvious problems
  - Arise if one process faster than other
  - Buffer size critical to avoid such problems

Shared Double Buffer

- Scheme says two processes share two common sets of
  - Memory locations
- Called ping-pong buffering scheme
  - Effective between processes running at different rates
- One buffer being filled while other being emptied
  - Consumer blocks on lack of data
  - Producer must still avoid over running buffer

Ring Buffer

- Scheme FIFO structure studied earlier
- Permits simultaneous input and output
  - Using head and tail pointers
- Must be careful to manage
  - Overflow
  - Underflow

<u>*Mailbox*</u>

- Mutually agreed upon memory location
  - Two or more tasks use to pass data
- Tasks rely on main scheduler to permit access
  - *Post* operation for write
  - *Pend* operation for read
- Pend operation different from poll
  - Poll task continually interrogates variable
  - Pend task suspended while data not available
- Variety of things passed
  - Single bit
    - Flag
  - Single data word
  - Pointer to data buffer
- In most implementations
  - Pend operation empties mailbox
    - If several tasks pending on flag
      - Enabled task resets flag
      - Blocks multiple accesses to resource
        - On single flag
- Some implementations
  - Permit queue of pending elements
    - Rather than single entry
  - Such scheme may be useful
    - Multiple independent copies of critical resource

Messages

- Message exchange is another means for communication
- Now starting to move more into distributed systems

- Called *interprocess communication* facility (IPC)
- Note IPC is not mutually exclusive with shared memory
- Idea to permit processes to communicate
  - Without resorting to shared variables
  - Particularly in different address spaces

IPC provides two operations

- Send
- Receive

Messages may be fixed or variable size

Basic Structure

- If processes P1 and P2 wish to communicate
  - Must
    - Send and receive messages
    - Establish a communication link

- Questions
  - Variety of questions one may ask
    - How to establish link
    - Can link be associated with multiple processes
    - How many links between pair or process
    - What is link capacity and are there buffers
    - What is message size
    - Are links
      - Unidirectional
      - Bi-directional

- Implementation methods
  - Direct / Indirect communication
  - Symmetric / asymmetric communication
  - Auto or explicit buffering
  - Send by copy or reference
  - Fixed or variable sized messages

- Let's look at several of these
- *Communication*
  - <u>Direct</u>
    - Each process must explicitly name sender / receiver of message
    - Messages logically of form
      - send (P1, message) // send message to P1
      - receive (P2, message) // receive message from P2
    - Link properties

Link automatically established between every pair of processes

Processes need ony know each others identity

Link associated with only two processes

Between each pair

Only single link

Link may be

Uni/bi directional

Example

Consider skeletal structure

Between producer P1 and consumer P2

```
repeat
    ...
    produce item in nextP1
    ...
    send (P2, nextP1)
until forever
```

```
repeat
    ...
    receive(P1, nextP2)
    ...
    consume item in nextP2
until forever
```

Observe scheme uses

Symmetrical addressing

Sender and receiver must name each other

If want asymmetric; addressing

Sender only names recipient

Disadvantage

Ties process name to implementation

<u>Indirect</u>

Messages sent / received from shared variable

Generally in form of mailbox

```
send (M0, message)       // send message to mailbox M0
receive (M0, message)    // receive message from mailbox M0
```

- Properties
  - Link established
    - Only if processes have shared mailbox
  - Link may be associated with multiple processes
  - May be multiple links between processes
  - Link may be uni/bi directional
- Consider 3 processes P0, P1, P2
  - All share M0
  - Let P0 send and P1 and P2 receive
    - Question - who gets message
  - Solution
    - Associate link with at most 2 processes
    - Allow only one process to receive at a time
    - Let system select receiver

- Mailbox owner
  - Process
    - If process owns mailbox
      - Can distinguish between
        - Owner
          - Who can only receive
        - User
          - Who can only send
      - Since each mailbox has unique owner
        - No ambiguity
  - System
    - Exists independent of any process
    - OS provides mechanism for process to
      - Create new mailbox
      - Send / receive messages through mailbox
      - Destroy mailbox
    - Creating process
      - May pass access privleges
      - Share mailbox
    - Must manage memory associated with mailboxs
      - For which no process has access rights

Buffering

Establishes number of messages

Temporarily reside in link

Three possibilities

Zero capacity

Link cannot store message

Sender must wait for receiver to accept message

Called rendez vous

Bounded capacity

Message queue has length n

If space remaining

Sender can place message in queue

Continue

Else

Sender must wait for space

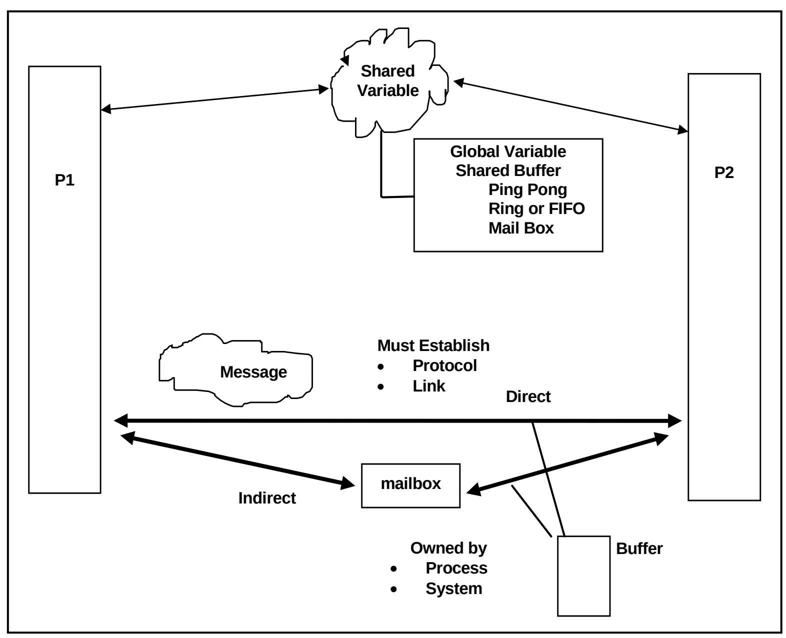
Unbounded

Potentially infinite length

Sender can post message

Continue

No wait



Thread Synchronization

Co-operating threads

One that can affect or be affected by another threads

May directly share logical address space

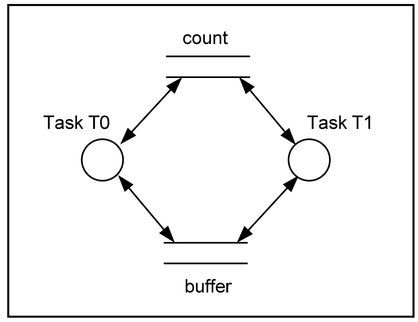
Code and data

Be allowed to share data only

Through files

Concurrent access to shared data

Can result in data inconsistency



Critical Sections

Consider following problem and code fragments

Exchanging messages through bounded buffer

Allow n items in buffer

Algorithm says

```
Producer
    If not full
        add item
        increment count
    else
        wait until space
```

```
Consumer
    If item
        get item
        decrement count
    else
        wait until item
```

```
Producer
repeat
    ...
    produce an item in nextP1
    while (count == n);  //  buffer full

    buffer[in] = nextP1;
    in = (in + 1) % n;
    count++;
until forever
```

```
Consumer
repeat
    while (count ==0);  //  buffer empty

    nextP2 = buffer[out];
    out = (out+1) % n;
    count--;
    ...
    consume nextP2;
    ...
until forever
```

Problem

Value of count

Depends upon who accesses variable

May be any of 3 different values

Variable count is critical variable

Within P1 or P2

Denoted *critical section*

Critical section in general

Section of code in which process is changing common variables

File

Table

etc

While process in critical section

Want to prevent access by all other processes

Termed *mutual exclusion*

Abstractly may represent code as

```
repeat
    entry section
        critical section
    exit section
        remainder section
until forever
```

Semaphores

Solution to critical section problem must satisfy following requirements

mutual exclusion

If process P1 is in critical section

No other process may enter

progress

If no process in critical section and some process wish to enter

Only processes not in remainder section

Can participate in decision

Decision cannot be postponed indefinitely

bounded waiting

Must be bound on number of times other processes can enter critical section

After a process has made a request to enter

Before request granted

Methodology to protect critical section suggested by Dijkstra

- Called *semaphore*
- Semaphore
  - Integer or Boolean variable - S
    - Accessed only through two atomic operations
      - wait - P(S)
      - signal - V(S)
  - Operations may be defined by following code fragments

```
wait(s)
{
    while (s);
    s = TRUE;
}
```

```
signal(s)
{
    s = FALSE;
}
```

s is initialized to FALSE

These may now be used as

```
Process 1
{
    …
    wait(s)
        critical section
    signal(s)
    …
}
```

```
Process 2
{
    …
    wait(s)
        critical section
    signal(s)
    …
}
```

Consider two concurrently running processes p1 and p2 let

- p1
  - Contain statement s1
- p2
  - Contain statement s2

We require s1 be executed before s2

- Thus define semaphore sync

Initialize sync to TRUE

```
p1
      ...
      s1
      signal(sync)      // signal
      ...
```

```
P2
      ...
      wait(sync)        // wait
      s2
      ...
```

Observe

- Because synch initialized to TRUE
  - p2 will execute s2 only after
  - p1 executes s1

Spin Lock

- Main disadvantage of semaphores as described
  - When wait encountered
    - Encountering process blocked
      - Must loop continuously while waiting
    - Called *busy waiting*
    - Waiting processes waste CPU cycles while waiting
      - Other process could use productively
- Such a semaphore called *spinlock*
  - Because process spins while waiting for lock
  - Advantage of spinlock
    - No context switch
      - Can take long time
    - If lock expected to be held for short time
      - Spinlock useful

To overcome need for busy waiting

- Modify definition of semaphore operations

When process executes wait operation

- If semaphore TRUE
  - Must wait

Rather than wait process can *block* itself

- Block operation places self in waiting queue
  - Associated with semaphore
- Process state changed to waiting
- Control transferred to scheduler

Blocked process should be restarted

- Some other process executes signal operation
- Process
  - Restarted
    - By *wakeup* operation
    - Places process in ready state
  - Placed in ready queue

Semaphore now defined as follows

- s initialized to 1

```
wait(s)
{
    s = s-1;  // on first pass s == 0
    if (s < 0)
    {
        add process to waiting queue;
        block;
    }
}
```

```
signal(s)
{
    s = s+1;
    if (s <=0)
    {
        remove process from waiting queue;
        wakeup(p);
    }
}
```

- Note semaphore now has integer value
  - block operation suspends invoking process
  - wakeup resumes execution of blocked process
  - Both operations provided by operating system calls
- Observe
  - Waiting list can be implemented by linked list
    - Perhaps implement as FIFO queue

Mutexes and Counting Semaphores

- Semaphores we've looked at called *binary semaphores*
  - Can take on either one of two values
- *Mutex*
  - Binary
  - Used to serialize access to reentrant code
  - Allows only one thread into controlled code section
  - **Example**
    - Key to toilet
- *Semaphore*
  - Counting
  - Can take on more than two values
    - Like previous example
  - Used to protect pools of resources or track number or resources
  - Restricts number of simultaneous users (threads) of shared resource
  - **Example**
    - Number of keys to toilet

- Working with a counting semaphore - let's call these
  - wait - wait(s)
  - signal - sig(s)

```
wait(s)
{
    s--;
    if (s<0)
    add this process to queue;
    block;
}
```

```
sig(s)
{
    s++;
    if (s<=0)
    remove a process Pi from queue;
    wakeUp(Pi);
}
```

- Each semaphore has
  - Integer value
  - List of associated processes
- When process must wait on semaphore
  - Added to list of processes

Signal

Removes process from list

Awakens it

Operations may be defined by following code fragments

Bounded Buffer Problem

Let's look at one classic synchronization problem

Consider we have a pool of n buffers

Each can hold one item in this example

We define semaphores

mutex

Provides mutual exclusion for accesses to buffer pool

Initialized to value 1

Empty - *semaphore*

Count number of empty buffers

Initialized to n

Full - *semaphore*

Count number of full buffers

Initialized to 0

Code fragments illustrated as

```
Producer
    repeat
        ...
        produce an item anItem
        ...
        wait(empty);  //  check for non zero
                      //  dec empty cnt
        wait(mutex);
        ...
            add anItem to buffer nextProd;
        ...
        signal(mutex);
        signal(full);  //  inc full cnt
        ...
    until false
```

```
Consumer
    repeat
        wait(full);  //  check for non zero
                     //  dec full cnt
        wait(mutex);
        ...
            remove anItem from buffer nextCons;
        ...
        signal(mutex);
        signal(empty);  //  inc empty cnt
        ...
        consume item anItem
        ...
    until false
```

Readers and Writers Problem

- Data object may be shared among several concurrent processes
- Some may want to read and others may want to write
- Processes referred to as
  - Readers
  - Writers
- If 2 readers access simultaneously
  - No problem
- If writer and any other process access simultaneously
  - Big problem
- Referred to as *readers* - *writers* problem
  - Several variations
    - <u>First readers-writers</u>
      - No reader waits
        - Unless writer has obtained access of shared variable
    - <u>Second readers-writers</u>
      - Once writer ready
        - Performs write as soon as possible
      - If writer waiting
        - No new reader started
- Solution to first readers-writers problem
  - Define
    - Semaphores - mutex, wrtSem
      - Initialize to 1
      - mutex - ensure mutual exclusion when readcount updated
      - wrtSem - mutual exclusion for writers
    - integer - numReaders
      - Initialize to 0
      - numReaders - count of readers currently accessing shared variable
  - Code fragment given as:

Writer Process

```
wait(wrtSem);                // wait for wrtSem == 1
                             // wrtSem = 0
    ...
    perform writing;
    ...
signal(wrtSem);              // wrtSem = 1
    ...
```

```
Reader Process
    wait(mutex);                   //  wait while mutex == 1
                                   //  mutex = 0
    numReaders++;                      //  inc number of readers
    if (numReaders ==1)            //  if i'm the only reader
        wait(wrtSem);              //  make sure no writers
                                   //  wrtSem = 1
    signal(mutex);                 //  mutex = 0
        ...
    Perform reading;
        ...
    wait(mutex);                   //  wait for mutex == 1
                                   //  mutex = 0
    numReaders--;                  //  dec number of readers
    if (numReaders ==0)            //  no readers
        signal(wrtSem);            //  wrtSem = 0
    signal(mutex);                 //  mutex = 0
    ...
```

Note

- If writer in critical section and n readers waiting
  - One reader queued on wrtSem
  - n-1 readers queued on mutex
- If writer executes signal(wrtSem)
  - May resume
    - Waiting readers
    - One waiting writer
  - Decision made by scheduler

Monitors

- Semaphores we've studied
  - Fundamental synchronism mechanism
  - However low-level mechanism
    - Easy to make errors with them

- Monitors are program modules
  - Offer more structure than semaphores

    - Implementation can be as efficient

- Monitors
  - Data abstraction mechanism
  - Encapsulate
    - Representation of abstract object
  - Provide public interface
    - Only means by which
      - Internal data may be manipulated
  - Contains variable to
    - Store object’s state
    - Procedures that implement operations on object
  - We satisfy mutual exclusion
    - By ensuring
      - Procedures in same monitor
        - Cannot execute simultaneously
  - Conditional synchronization
    - Provided through condition variables

- Monitor used to group
  - Representation and implementation
    - The interface and body
      - Of shared resource
  - Has *interface* and *body*
    - Interface
      - Specifies operations and behaviour provided by resource
    - Body
      - Contains
        - Variables
          - Represent state of resource
        - Procedures
          - Procedures
            - Implement operations specified in interface

Schematically we have

```
monitor monName
{
    initialization statements  //analogous to constructor
    procedures
    permanent variables
}
```

- Procedures implement
  - Visible operations
- Permanent variables
  - Shared by all processes
    - In the monitor
    - Like statics in C++ or pool variables in Smalltalk
  - Denoted permanent
    - Retain values on exit
      - As long as monitor exists
- Procedures
  - May have local variables

By virtue of being an Abstract Data Type
- Monitor is a distinct scope
  - Only procedure names – this is the public interface
    - Visible outside of monitor
  - Permanent variables
    - Can only be changed
      - Through one of the visible procedures
  - Statements within monitor
    - Cannot affect variables outside monitor
      - In different scope
  - Permanent variables
    - Initialized before any procedure called
    - Accomplished by
      - Executing initialization procedures
        - When monitor instance created

- Monitor sounds very similar to C++ class
  - Major difference
    - Monitor shared by multiple concurrently executing processes or threads
  - Consequently
    - Threads or processes using monitor
      - May require
        - *Mutual exclusion*
          - To monitor variables
        - *Synchronization*
          - To ensure monitor state conducive to continued execution
  - Mutual exclusion
    - Usually implicit
  - Synchronization
    - Implemented explicitly
      - Different processes require different forms of synchronization
    - Implementation achieved through
      - *Condition variables*
        - Shared variables discussed earlier

- Monitor procedure
  - Called by external process or thread
  - A procedure is active
    - If a thread or process executing
      - Statement in procedure
  - At most one instance of monitor procedure
    - Active at any one time
  - Cannot have
    - Two different procedures invoked
      - or
    - Two invocations of same procedure
  - By definition
    - Execute with mutual exclusion
      - Ensured by
        - Language
        - Library
        - Operating system

- Generally implemented
  - Locks or semaphores
  - Inhibiting certain interrupts

Condition Variables

- Condition variables used as part of synchronization process
  - Used to delay thread or process that
    - Cannot safely continue
      - Until monitor's state satisfies some Boolean condition
  - Used to awaken delayed process
    - Once condition becomes true

- Condition variable
  - Instance of variable of type *cond*
    - cond myCondVar;
  - Can only be declared inside monitor
  - Value of condition thus it represents a queue
    - Queue of delayed processes
  - Initially queue is empty
  - Value can only be accessed indirectly
    - Much like private variables in C++ or Java
    - Test state
      - `empty(myCondVar);`
    - Thread can block on a condition variable
      - `wait(myCondVar);`
      - Execution of wait causes process to
        - Move to rear of queue
        - Relinquish exclusive access to monitor
    - Blocked process awakened
      - `signal(myCondVar);`
      - Execution of signal causes thread
        - At head of queue to awaken

  - Execution of signal
    - Seems to cause dilemma
      - Upon execution two processes have potential to execute
        - Awakened thread

Signaling thread

Contradicts requirement

Only single thread active in monitor at once

Two possible paths for resolution

- Signal and continue

  Signaling thread continues

  Awakened process resumes at some delayed time

  Considered nonpreemptive

  Process executing signal

  Retains exclusive control of the monitor

- Signal and wait

  Considered to be preemptive

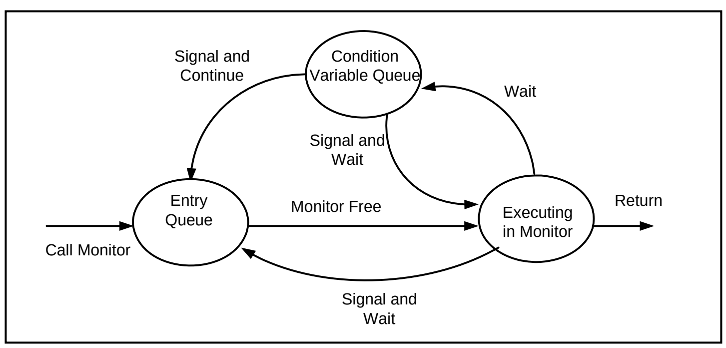
  Process executing signal

  Relinquishes control and passes lock

  To awakened process

  Awakened process preempts signaling process

Can describe process with following state diagram



Operation / synchronization occurs as follows

Thread *calls* monitor procedure

If another thread executing in monitor

Caller placed into *entry queue*

When monitor becomes free

Result of *return* or *wait*

One thread moves from entry queue into monitor

Else passes through entry queue

Begins executing immediately

If thread executes wait on a condition variable

While executing in monitor

Thread enters queue associated with that variable

When thread executes

Signal and Continue on a condition variable

Thread at head of associated queue

Moves to entry queue

Signal and Wait on a condition variable

Thread at head of associated queue

Moves to monitor

Thread executing in monitor

Moves to entry queue

Bounded Buffer Problem with Monitor

Let’s look at one classic synchronization problem

Looked at earlier with semaphores

Implemented with monitor

Consider we have a pool of n buffers

Each can hold one item in this example

We define a monitor *boundedBuffer*

We define condition variables

notEmpty

Signaled when buffer count > 0

Tracks empty buffers

initialized to 0

notFull

Signaled when buffer count < n

Tracks full buffers

Initialized to 0

We define procedures

put(data)

Puts data into a buffer

When space available

get(data)

Gets data from a buffer

When data available

We define the protected entity

bufferPool

We can implement our monitor as follows

```
monitor boundBuffer
    bufferPool;
    count = 0;
    cond notEmpty;          //  signaled when count > 0
    cond notFull;           //  signaled when count < n

    put(anItem)
    {
        while(count == n) wait (notFull);
            put anItem into a buffer
            signal (notEmpty);
    }
    get(anItem)
    {
        while(count == 0) wait (notEmpty);
            get anItem from a buffer
            signal (notFull);
    }
```

Code fragments illustrated as

```
Producer
    repeat
        ...
        produce an item anItem
        ...
        boundBuffer.put(anItem)
        ...
    forever
```

```
Consumer
    repeat
        ...
        boundBuffer.get(anItem)
        …
        consume item anItem
        ...
    forever
```

Deadlocks and Starvation

Deadlocks

Implementation of semaphore or monitor with waiting queue

- Can result in situation in which 2 or more processes
  - Wait indefinitely
  - Called *deadlock*

Consider 2 processes P0 and P1

- Let each process have 2 semaphores
  - S1 and S2
  - May be resources each needs
    - R1 and R2
    - Need both to continue
  - Let R1 and R2 be set to value 1

- Let
  - P0 set wait(S1) // wait for R1 decrement S1 (=0)
  - P1 set wait(S2) // wait for R2 decrement S2 (=0)

- Now let
  - P0 set wait(S2) // wait for R2 decrement S2 (=-1)
  - P1 set wait(S1) // wait for R1 decrement S1 (=-1)

- At this point
  - P0 must wait for signal(S2)
  - P1 must wait for signal(S1)
  - These operations cannot be executed
    - Processes blocked
    - Every process in set waiting for event
      - Possible only by another member in set

Will discuss in much greater detail shortly

Starvation

Problem called *starvation* can occur

- Process waiting within semaphore
- Other processes added or removed
  - LIFO order

Events and Signals

- Some languages provide mechanisms for handling
  - Asynchronous events
- Provides software interrupt
  - Generally used for exceptions
    - Divide by zero
    - Arithmetic overflow
    - etc.
- In addition to built in procedures
  - Some permit user defined procedures to be
    - Provided and executed
      - ANSI-C

  - Provides signal and raise
    - Signal
      - Software interrupt handler
      - Responds to exceptions indicated by raise
    - Raise
      - Mechanism to signal an exception or event
  - Both implemented as function calls
  - Passing pointers to functions
    - Can handle variety of events or exceptions