Chapter 8

Basic Synchronization Principles

Need for Synchronization

- Multiprogramming
  - ➔ Multiple concurrent, independent processes
  - ➔ Those processes might want to coordinate activities

```
                shared x, y

Proc A {                          Proc B {
while (true) {                    while (true) {
       <compute A1>                      read(x)
       write(x)                          <compute B1>
       <compute A2>                      write(y)
       read(y)                           <compute B2>
       }                                 }
}                                 }
```

- Clearly, synchronization is needed if
  - A wants B to read `x` <u>after</u> it writes it & <u>before</u> it re-writes

Barriers to providing synchronization

- What are the barriers to providing good synchronization capabilities ?
  - No widely accepted parallel programming languages
    - CSP
    - Linda
  - No widely use paradigm
    - How do you decompose a problem ?
  - OS only provides minimal support
    - Test and Set
    - Semaphore
    - Monitor

Critical Section Problem

```
shared float balance;

/* Code schema for p1 */              /* Code schema for p1 */
..                                    ..
balance = balance + amount;           balance = balance - amount;
..                                    ..

  /* Schema for p1 */                     /* Schema for p2 */
  /*  X == balance */                     /*  X == balance */
     load R1, X                              load R1, X
     load R2, Y                              load R2, Y
     add R1, R2                              sub R1, R2
     store R1, X                             store R1, X
```

Critical Section Problem...

```
/* Schema for p1 */                 /* Schema for p2 */
     ⎧ load R1, X  ⎫                     ⎧ load R1, X  ⎫
     ⎪ load R2, Y  ⎭ 1               4   ⎩ load R2, Y  ⎪
  5  ⎨ add R1, R2  ⎫                     ⎧ sub R1, R2  ⎬ 2
     ⎩ store R1, X ⎭ 3               6   ⎩ store R1, X ⎭
```

- Suppose:
  - Execution sequence : 1, 2, 3
    - Lost update : 2
  - Execution sequence : 1, 4, 3 ,6
    - Lost update : 3
- Together => non-determinacy
- Race condition exists

Using Shared Global Variables – Ver 1

```
Shared integer: processnumber <= 1;

procedure processone;                      procedure processtwo;
begin                                      begin
  while true do                              while true do
    begin                                      begin
      while processnum == 2 do;  ← Hard wait     while processnum == 1 do;  ← Hard wait
      criticalsectionone;                        criticalsectiontwo;
      processnumber := 2;                        processnumber := 1;
      otherstuffone;                             otherstufftwo;
      end                                        end
  end                                        end
```

Single global variable forces **lockstep synchronization**

Using Shared Global Variables – Ver 2

```
Shared boolean: p1inside <= false, p2inside <= false;

procedure processone;
  begin
     while true do
       begin
         while p2inside do;
         p1inside := true;
         criticalsectionone;
         p1inside := false;
         otherstuffone;
       end
  end

procedure processtwo;
  begin
     while true do
       begin
         while p1inside do;
         p2inside := true;
         criticalsectiontwo;
         p2inside := false;
         otherstufftwo;
       end
  end
```

- Process 1 & 2 can both be **in the critical sections at the same time** Because Test & Set operations are **not atomic**

  ==> Move setting of p1inside/p2inside before test

Using Shared Global Variables – Ver 3

```
Shared boolean: p1wantsin <= false, p2wantsin <= false;

procedure processone;
  begin
     while true do
       begin
         p1wantsin := true;
         while p2wantsin do;
         criticalsectionone;
         p1wantsin := false;
         otherstuffone;
       end
  end

procedure processtwo;
  begin
     while true do
       begin
         p2wantsin := true;
         while p1wantsin do;
         criticalsectiontwo;
         p2wantsin := false;
         otherstufftwo;
       end
   end
```

- **Deadlock** can occur if both sets flag at the same time

  ==> Need a way to break out of loops.....

Wherein Lies the Problem?

- Problem stems from interruption of software-based process while executing critical code (low-level)
- Solution
  - Identify critical section
  - *Disable interrupts* while in Critical Section

```
shared double balance;
```

```
/* Program for P1 */
DisableInterrupts();
balance = balance + amount;  } CS
EnableInterrupts();
```

```
/* Program for P2 */
DisableInterrupts();
Balance = balance - amount;  } CS
EnableInterrupts();
```


Using Interrupts...

- This works *BUT*...
  - Allows process to disable interrupts for arbitrarily long time
  - What if I/O interrupt needed ?
  - What if one of the processes is in infinite loop inside the Critical Section
- Let's examine the use of Shared Variables again….

Using Shared Variable to Synchronize

```
shared boolean lock <= FALSE;
shared float balance;
```

```
/* Program for P1 */
..
/* Acquire lock */
while(lock) {NULL;};
lock = TRUE;
/* Execute critical section */
balance = balance + amount;
/* Release lock */
lock = FALSE;
..
```

```
/* Program for P2 */
..
/* Acquire lock */
while(lock) {NULL;};
lock = TRUE;
/* Execute critical section */
balance = balance - amount;
/* Release lock */
lock = FALSE;
..
```

`lock == FALSE`
=> No process in CS
=> Any process can enter CS

`lock == TRUE`
=> One process in CS
=> No other process admitted to CS

Synchronizing Variable…

- What if P1 interrupted after lock Set to TRUE
  => P2 cannot execute past while does hard wait
  => Wasted CPU time
- What if P1 interrupted after Test, before Set
  => *P1 & P2 can be in the CS at the same time !!!*
- Wasted CPU time is bad, but tolerable…..
  Critical Section Violation **cannot** be tolerated
  ==> Need Un-interruptable “Test & Set” operation

Un-interruptable Test & Set

```
enter(lock) {
  disableInterrupts();
  /* Loop until lock TRUE */
  while (lock) {
    /* Let interrupts occur */
    enableInterrupts();
    disableInterrupts();
  }
  lock = TRUE;
  enableInterrupts();
}
```

Enable interrupts so that the OS, I/O can use them

Re-disable interrupts when ready to test again

```
exit(lock) {
  disableInterrupts();
  lock = FALSE;
  enableInterrupts();
}
```


Un-interruptable Test & Set...

- Solution

P1

```
   enter(lock);
CS{ balance = balance + amount;
   exit(lock);
```

P2

```
   enter(lock);
CS{ balance = balance - amount;
   exit(lock);
```

- Note
  - CS is totally bounded by enter/exit
  - P2 can still wait (waisted CPU cycles) if P1 is interupted after setting lock (i.e., entering critical section), but
  - **Mutual exclusion is achieved!!!!!**
- Does not generalize to multi-processing

Protecting Multiple Components

```
Shared: list L,
        boolean ListLK <= False;
        boolean LngthLK <= False;
```

```
/* Program for P1 */
enter(listLK);
   <delete element>;
exit(listLK);
   <intermediate comp.>;
enter(lngthLK);
   <update length>;
exit(lngthLK);
```

```
/* Program for P2 */
enter(lngthLK);
   <update length>;
exit(lngthLK);
<intermediate comp.>;
enter(listLK);
   <delete element>;
exit(listLK);
```

- Use enter/exit to update structure with 2 pieces if information
- ***But* try to *minimize time component locked out***

Protecting Multiple Components: 1st try

```
Shared: list L,
        boolean ListLK <= False;
        boolean LngthLK <= False;
```

```
/* Program for P1 */
enter(listLK);
   <delete element>;
exit(listLK);
☼ <intermediate comp.>;
enter(lngthLK);
   <update length>;
exit(lngthLK);
```

```
/* Program for P2 */
enter(lngthLK);
   <update length>;
exit(lngthLK);
   <intermediate comp.>;
enter(listLK);
   <delete element>;
exit(listLK);
```

Suppose: P1… ☼ ; P2 runs & finishes; P1 ☼ …….

Any access to lngth vble during "intermediate comp." will be incorrect !!!

=> Programming Error: List and variable need to be updated together

Protecting Multiple Components: 2^{nd} try

```
Shared: list L,
        boolean ListLK <= False;
        boolean LngthLK <= False;
```

```
/* Program for P1 */

enter(listLK);
   <delete element>;
 ☼ <intermediate comp.>;
enter(lngthLK);
   <update length>;
exit(listLK);
exit(lngthLK);
```

CS_1 CS_2

```
/* Program for P2 */

enter(lngthLK);
   <update length>;
 ⊗ <intermediate comp.>;
enter(listLK)
   <delete element>;
exit(lngthLK);
exit(listLK);
```

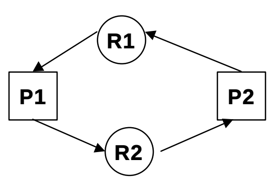
CS_2 CS_1

- Suppose: P1...☼ ;
  P2 runs to ⊗ and blocks ;
  P1 starts & blocks on "enter"
  => ***DEADLOCK***

Deadlock

- Deadlock
  - When 2 or more processes get into a state whereby each is holding a resource requested by the other

P1	P2
.	.
Request $Resource_1$	Request $Resource_2$
.	.
Request $Resource_2$	Request $Resource_1$
.	.




```
P1 requests and gets R1
interrupt
P2 requests and gets R2
interrupt
P1 requests R2 and blocks
P2 requests R1 and blocks
```

Solution to Synchronization

- The previous examples have illustrated 2 methods for synchronizing / coordinating processes
  - Interrupt
  - Shared variable
- Each has its own set of problems
  - Interrupt
    - May be disabled for too long
  - Shared variable
    - Test, then set – interruptable
    - Non-interruptable – gets complex
- Dijkstra introduces a 3rd and much more preferable method
  - Semaphore

Semaphore

- Dijkstra, 1965
- Synchronization primitive with <u>no busy waiting</u>
- It is an integer variable changed or tested by one of the two <u>indivisible</u> operations
- Actually implemented as a protected variable type

```
var x : semaphore
```

Semaphore operations

- **P** operation ("wait")
  - Requests permission to use a critical resource

```
S := S – 1;
if (S < 0) then
      put calling process on queue
```

- **V** operation ("signal")
  - Releases the critical resource

```
S := S + 1;
if (S <= 0) then
      remove one process from queue
```

- Queues are associated with each semaphore variable

Semaphore : Example

```
Critical resource    T
Semaphore            S ← initial_value
Processes            A,B
```

Process A

```
.
P(S);
<CS> /* access T */
V(S);
.
```

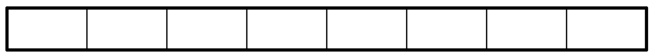
Process B

```
.
P(S);
<CS> /* access T */
V(S);
.
```

Semaphore : Example...

```
var S : semaphore ← 1
```

Queue associated with S



Value of S : 1

Process A	Process B	Process C
`P(S);`	`P(S);`	`P(S);`
<**CS**>	<**CS**>	<**CS**>
`V(S);`	`V(S);`	`V(S);`

Types of Semaphores

- Binary Semaphores
  - Maximum value is 1
- Counting Semaphores
  - Maximum value is greater than 1
- Both use same P and V definitions
- Synchronizing code and initialization determines what values are needed, and therefore, what kind of semaphore will be used

Using Semaphores

```
Shared semaphore mutex <= 1;

proc_1() {                              proc_2() {
  while(true) {                           while(true) {
     <compute section>;                      <compute section>;
     P(mutex);                               P(mutex);
       <critical section>;                      <critical section>;
     V(mutex);                               V(mutex);
     }                                       }
  }                                       }
```

(1) P1 => P(mutex)
Decrements; <0 ?; NO (0);
P1 Enters CS;
P1 interrupted

Non-Interruptable "Test & Sets"

(2) P2 => P(mutex)
Decrements; <0 ?; YES (-1)
P2 **blocks** on **mutex**

(3) P1 finishes CS work
P1 => V(mutex);
Increments; <=0 ?; YES (0)
P2 woken & proceeds

Using Semaphores - Example 1

```
Shared semaphore mutex <= 1;

proc_0() {                          proc_1() {
...                                 …
P(mutex);                           P(mutex);
balance = balance + amount;         balance = balance - amount;
V(mutex);                           V(mutex);
...                                 ...
}                                   }
```

Suppose P1 issues P(mutex) first ……
Suppose P2 issues P(mutex) first …… } No Problem

Note: Could use Interrupts to implement solution,
But (1) with interrupts masked off, what happens if a prior I/O request is satisfied
(2) Interrupt approach would not work on Multiprocessor

Using Semaphores – Example 2

Shared semaphore: s1 <= 0, s2 <= 0;

Note: values started at 0… ok?

```
proc_A() {
  while(true) {
    <compute A1>;
    write(x);
    V(s1);
    <compute A2>;
    P(s2);
    read(y);
  }
}
```

A signals B that "write to x" has completed

A blocks until B signals

```
proc_B() {
  while(true) {
    P(s1);
    read(x);
    <compute B1>;
    write(y);
    V(s2);
    <compute B2>;
  }
}
```

B blocks till A signals

B signals A that "write to y" has completed

- Cannot use Interrupt disable/enable here because we have *multiple distinct synchronization points*
- Interrupt disable/enable can only distinguish 1 synchronization event
- **Therefore, 2 Semaphores**

Using Hardware Test & Set [TS(s)] to Implement Binary Semaphore "Semantics"

```
boolean s = FALSE;          semaphore s = 1;
...                         ...
while( TS(s) );      ?≡     P(s);
<critical section>          <critical section>
S = FALSE;                  V(s);
...                         ...
```

- **TS(s)**
  - **Test s**
  - **Set s to True**
  - **Return original value**

Uninterruptable

Note: No actual queueing, each process just "hard waits"

Counting Semaphores

- Most of our examples have only required Binary Semaphore
  - Only 0 or 1 values
- But synchronization problems arise that require a more general form of semaphores
- Use counting semaphores
  - Values : non-negative integers

Classical Problems

- Producer / Consumer Problem
- Readers – Writers Problem

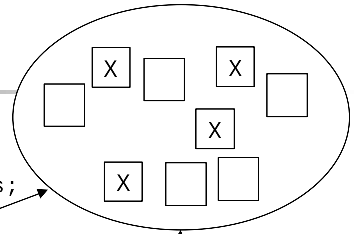
Producer / Consumer Problem (Classic)

- Critical resource
  - Set of message buffers
- 2 Processes
  - Producer : Creates a message and places it in the buffer
  - Consumer : Reads a message and deletes it from the buffer
- Objective
  - Allow the producer and consumer to run concurrently

P/C…

- Constraints
  - Producer must have a non-full buffer to put its message into
  - Consumer must have a non-empty buffer to read
  - Mutually exclusive access to Buffer pool
- Unbounded Buffer problem
  - Infinite buffers
  - Producer never has to wait
  - Not interesting nor practical
- Bounded Buffer Problem
  - Limited set of buffers

P/C - Solution




```
Shared Full: semaphore ← 0;
       Empty semaphore ← MaxBuffers;
       MEPC: semaphore ← 1;
```

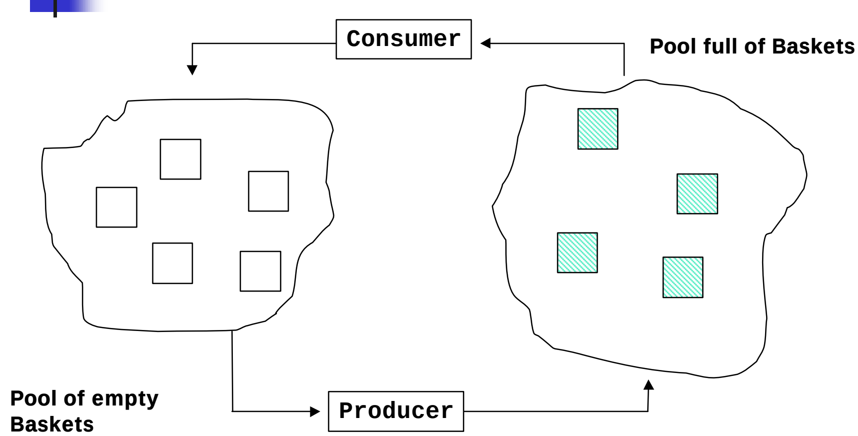
Producer

```
Begin
...
P(Empty);
P(MEPC);
<add item to buffer>
V(MEPC);
V(Full);
...
End;
```

Consumer

```
Begin
...
P(Full);
P(MEPC);
<remove item from buffer>
V(MEPC);
V(Empty);
...
End;
```


P/C – Another Look



P/C – Another Look

- 9 Baskets – Bounded
- Consumer – Empties basket
  - Can *only* remove basket from Full Pool, if one is there
    => Need "full" count
  - Emptys basket and places it in Empty pool
- Producer – Fills basket
  - Can *only* remove basket from Empty pool, if one is there
    => Need "empty" count
  - Fills basket and places it in Full pool

P/C - Another Look

```
Shared semaphore: Emutex = 1, Fmutex = 1; full = 0,  empty = 9;
Shared buf_type: buffer[9];
```

```
producer() {
  buf_type *next, *here;
  while(True) {
    produce_item(next);
    P(empty); /*Claim empty buffer*/
    P(Emutex); /*Manipulate the pool*/
    here = obtain(empty);
    V(Emutex);
    copy_buffer(next, here);
    P(Fmutex); /*Manipulate the pool*/
    release(here, fullpool);
    V(Fmutex); /*Signal full buffer*/
    V(full);
  }
}
```

```
consumer() {
  buf_type *next, *here;
  while(True) {
    P(full); /*Claim full buffer*/
    P(Fmutex); /*Manipulate the pool*/
    here = obtain(full);
    V(Fmutex);
    copy_buffer(here, next);
    P(Emutex); /*Manipulate the pool*/
    release(here, emptypool);
    V(Enmutex); /*Signal empty buffer*/
    V(empty);
    consume_item(next);
  }
}
```

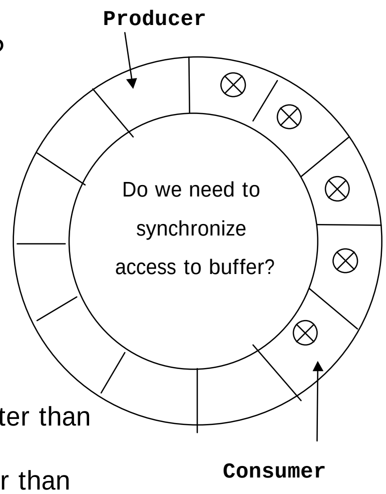
P/C - Example

- How realistic is PCP scenario?
- Consider a circular buffer
  - 12 slots
  - Producer points at next one it will fill
  - Consumer points at next one it will empty
- Don t want :

  Producer = Consumer

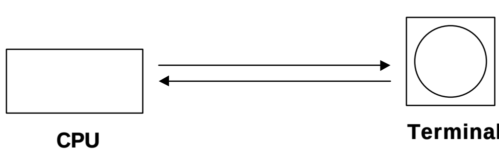
  => (1) Consumer “consumed” faster than producer “produced”, or

  (2) Producer “produced” faster than consumer “consumed”.



P/C – Real World Scenario

- CPU can produce data faster than terminal can accept or viewer can read

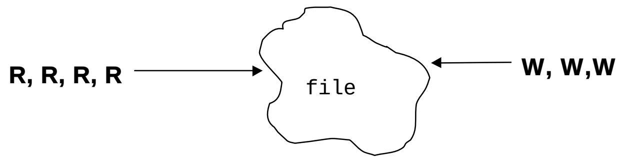


Communication buffers in both

Xon/Xoff Flow Control

Readers / Writers Problem (Classic)

- Multiple readers of the same file?
  - No problem
- Multiple writers to the same file?
  - Might be a problem writing same record
    => Potentially a 'lost update"
- Writing while reading
  - Might be a problem – read might occur while being written
    => Inconsistent data



Readers – Writers Problem

- Critical resource
  - File
- Consider multiple processes which can read or write to the file
- What constraints must be placed on these processes?
  - Many readers may read at one time
  - Mutual exclusion between readers and writers
  - Mutual exclusion between writers

Strong Reader Solution

```
Shared int: readCount = 0;
       semaphore: mutexRC = 1, writeBlock = 1;
```

```
reader(){
  while(TRUE) {
    P(mutexRC);
    readCount = readCount + 1;
    if (readCount == 1)
        P(writeBlock);
    V(mutexRC);
       access_file;
    P(mutexRC);
    readCount = readCount – 1;
    if (readCount == 0)
       V(writeBlock);
    V(mutexRC);
  }
}
```

```
writer(){
  while(TRUE) {
    P(writeBlock);
       access_file;
    V(writeBlock);
  }
}
```

This solution gives preference to **Readers**

If a reader has access to file and other readers want access, they get it… all writers must wait until all readers are done

Reader / Writers – Ver 2

- Create a Strong Writer
- Give priority to a waiting writer
- If a writer wishes to access the file, then it must be the next process to enter its critical section

Strong Writers Solution

Shared int: readCount = 0, writeCount = 0
semaphore: mutex1 = 1, mutex2 = 1, readBlock = 1, writePending = 1, writeBlock = 1;

```
reader(){
  while(TRUE) {
    P(writePending);
      P(readBlock);
        P(mutex1);
          readCount = readCount + 1;
          if (readCount == 1) then
            P(writeBlock);
        V(mutex1);
      V(readBlock);
    V(writePending);
      access file;
    P(mutex1);
      readCount = readCount – 1;
      if (readCount == 0) then
        V(writeBlock);
    V(mutex1);
  }
}
```

```
writer(){
  while(TRUE) {
    P(mutex2);
      writeCount = writeCount + 1;
      if (writeCount == 1) then
         P(readBlock);
    V(mutex2);
    P(writeBlock);
       access file;
    V(writeBlock);
    P(mutex2);
      writeCount = writeCount - 1;
      if (writeCount == 0) then
         V(readBlock);
    V(mutex2);
  }
}
```


Implementing Counting Semaphores

```
struct sempahore {
  int value = <initial value>;
  boolean mutex = FALSE;
  boolean hold = TRUE;
};
Shared struct semaphore s;
```

```
P(struct sempahore s) {
  while( TS(s.mutex) );
  s.value = s.value – 1;
  if (s.value < 0) {
    s.mutex = FALSE;
    while( TS(s.hold) );
  }
else {
   s.mutex = FALSE;
}
```

```
V(struct sempahore s) {
  while( TS(s.mutex) );
  s.value = s.value + 1;
  if (s.value <= 0) {
    while( !s.hold );
    s.hold = FALSE;
  }
  s.mutex = FALSE;
}
```