Chapter 8

Basic Synchronization Principles
Need for Synchronization

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

  \[\text{shared } x, y\]

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

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

- Clearly, synchronization is needed if
  - A wants B to read \(x\) \text{ after} it writes it \& \text{ before} 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
shared float balance;

/* Code schema for p1 */
.. balance = balance + amount;
..
/* Schema for p1 */
load R1, balance
load R2, amount
add R1, R2
store R1, balance

/* Code schema for p2 */
.. balance = balance - amount;
..
/* Schema for p2 */
load R1, balance
load R2, amount
sub R1, R2
store R1, balance
Critical Section Problem...

/* Schema for p1 */

\[
\begin{align*}
5 & \quad \{ \\
& \quad \text{load R1, balance} \quad 1 \\
& \quad \text{load R2, amount} \quad 2 \\
& \quad \text{add R1, R2} \quad 3 \\
& \quad \text{store R1, balance} \quad 4
\end{align*}
\]

/* Schema for p2 */

\[
\begin{align*}
4 & \quad \{ \\
& \quad \text{load R1, balance} \quad 1 \\
& \quad \text{load R2, amount} \quad 2 \\
& \quad \text{sub R1, R2} \quad 3 \\
& \quad \text{store R1, balance} \quad 4
\end{align*}
\]

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

Two processes want to access shared memory at the same time.

Taken from Modern Operating Systems, 2nd Ed, Tanenbaum, 2001
Using Shared Global Variables – Ver 1

Shared integer: processnumber = 1;

```c
void processone;
{
    while (true) {
        while (processnumber == 2) ;
        criticalsectionone;
        processnumber := 2;
        otherstuffone;
    }
}

void processtwo;
{
    while (true)
    {
        while (processnumber == 1) ;
        criticalsectiontwo;
        processnumber := 1;
        otherstufftwo;
    }
}
```

Single global variable forces lockstep synchronization
Using Shared Global Variables – Ver 2

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

```c
void processone;
{
    while (true) {
        while (p2inside) ;
        p1inside := true;
        criticalsectionone;
        p1inside := false;
        otherstuffone;
    }
}

void processtwo;
{
    while (true) {
        while (p1inside) ;
        p2inside := true;
        criticalsectiontwo;
        p2inside := false;
        otherstufftwo;
    }
}
```

- 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
void processone;
{
    while (true) {
        p1wantsin := true;
        while (p2wantsin)
        ;
        criticalsectionone;
        p1wantsin := false;
        otherstuffone;
    }
}

void processtwo;
{
    while (true) {
        p2wantsin := true;
        while (p1wantsin)
        ;
        criticalsectiontwo;
        p2wantsin := false;
        otherstufftwo;
    }
}

- **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

```c
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-interruptible Test & Set**

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

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

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

Re-disable interrupts when ready to test again
Un-interruptible Test & Set...

■ Solution

P1
enter(lock);
\[
\begin{align*}
\text{CS} & \{ \text{balance} = \text{balance} + \text{amount}; \\
& \text{exit(lock);}
\}
\]

P2
enter(lock);
\[
\begin{align*}
\text{CS} & \{ \text{balance} = \text{balance} - \text{amount}; \\
& \text{exit(lock);}
\}
\]

■ Note

■ CS is totally bounded by enter/exit
■ P2 can still wait (wasted CPU cycles) if P1 is interrupted 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\textsuperscript{nd} try

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

\begin{itemize}
\item Suppose: P1...\(\bigotimes\) ;
\item P2 runs to \(\bigotimes\) and blocks ;
\item P1 starts & blocks on “enter”
\end{itemize}

\[\Rightarrow \textbf{DEADLOCK}\]

CS 3204 - Arthur
Deadlock

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

**Diagram:**

```
P1
  .
  Request Resource₁
  .
  Request Resource₂
  .

P2
  .
  Request Resource₂
  .
  Request Resource₁
  .
```

- 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 – interruptible
    - Non-interruptible – gets complex

- Dijkstra introduces a 3\textsuperscript{rd} and much more preferable method
  - Semaphore
Semaphore

- Dijkstra, 1965

- Synchronization primitive with no busy waiting

- It is an integer variable changed or tested by one of the two indivisible operations

- Actually implemented as a protected variable type
  
  ```
  var x : semaphore
  ```
Semaphore operations

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

    \[
    S := S - 1;
    \]
    \[
    \text{if (} S < 0 \text{) then}
    \]
    \[
    \text{put calling process on queue}
    \]

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

    \[
    S := S + 1;
    \]
    \[
    \text{if (} S \leq 0 \text{) then}
    \]
    \[
    \text{remove one process from queue}
    \]

- Queues are associated with each semaphore variable
Semaphore: Example

Critical resource \( T \)
Semaphore \( S \leftarrow \text{initial}_\text{value} \)
Processes \( A, B \)

<table>
<thead>
<tr>
<th>Process A</th>
<th>Process B</th>
</tr>
</thead>
<tbody>
<tr>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>( P(S); )</td>
<td>( P(S); )</td>
</tr>
<tr>
<td>(&lt;\text{CS}&gt; /* access T */)</td>
<td>(&lt;\text{CS}&gt; /* access T */)</td>
</tr>
<tr>
<td>( V(S); )</td>
<td>( V(S); )</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>
### Semaphore: Example...

```plaintext
var S : semaphore ← 1

Queue associated with S

Value of S : 1
```

<table>
<thead>
<tr>
<th>Process A</th>
<th>Process B</th>
<th>Process C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P(S); )</td>
<td>( P(S); )</td>
<td>( P(S); )</td>
</tr>
<tr>
<td>(&lt;\text{cs}&gt;)</td>
<td>(&lt;\text{cs}&gt;)</td>
<td>(&lt;\text{cs}&gt;)</td>
</tr>
<tr>
<td>( V(S); )</td>
<td>( V(S); )</td>
<td>( V(S); )</td>
</tr>
</tbody>
</table>
```
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() {
    while(true) {
        <compute section>;
        P(mutex);
        <critical section>;
        V(mutex);
    }
}

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

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

(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() {
    ...
P(mutex);
balance = balance + amount;
V(mutex);
    ...
}

proc_1() {
    ...
P(mutex);
balance = balance - amount;
V(mutex);
    ...
}

Suppose P1 issues P(mutex) first ......  \{  No Problem  
Suppose P2 issues P(mutex) first ...... 

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);
  }
}

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

- 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”

```java
boolean s = FALSE;
...
while( TS(s) );
<critical section>
S = FALSE;
...
```

```java
semaphore s = 1;
...
?
P(s);
<critical section>
V(s);
...
```

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

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;

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

Begin
...
P(Full);
P(MEPC);
<remove item from buffer>
V(MEPC);
V(Empty);
...
End;
P/C – Another Look

Pool full of Baskets

Consumer

Pool of empty Baskets

Producer
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];

```c
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);
    }
}
```

```c
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(Emutex); /*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”.

Do we need to synchronize access to buffer?

Producer

Consumer
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(readBlock);
        P(mutex2);
        writeCount = writeCount - 1;
        if (writeCount == 0) then
            V(writeBlock);
        V(mutex2);
    }
}
Implementing Counting Semaphores

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

Shared struct semaphore s;

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