Chapter 9

High-level Synchronization
Concurrency

- Execute two or more pieces of code "at the same time"

Why?

- No choice:
  - Geographically distributed data
  - Interoperability of different machines
  - A piece of code must "serve" many other client processes
  - To achieve reliability

- By choice:
  - To achieve speedup
  - Sometimes makes programming easier (e.g., UNIX pipes)
## Possibilities for Concurrency

### Architecture:

<table>
<thead>
<tr>
<th>Uniprocessor with:</th>
<th>Program Style:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- I/O channel</td>
<td>Multiprogramming,</td>
</tr>
<tr>
<td>- I/O processor</td>
<td>multiple process system</td>
</tr>
<tr>
<td>- DMA</td>
<td>programs</td>
</tr>
<tr>
<td>Multiprocessor</td>
<td>Parallel programming</td>
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<tr>
<td>Network of processors</td>
<td>Distributed Programs</td>
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**CS 3204**
Examples of Concurrency in Uniprocessors

Example 1: Unix pipes

Motivations:
- fast to write code
- fast to execute

Example 2: Buffering

Motivation:
- required when two asynchronous processes must communicate

Example 3: Client/Server model

Motivation:
- geographically distributed computing
Operating System issues to Support Concurrency

- **Synchronization**
  - What primitives should OS provide?

- **Communication**
  - What primitives should the OS provide to the interface communication protocol?

- **Hardware Support**
  - Needed to implement OS primitives
Operating System issues to Support Concurrency…

- **Remote execution**
  - What primitives should OS provide?
    - Remote Procedure Call (RPC)
    - Remote Command Shell

- **Sharing address space**
  - Makes programming easier

- **Light-weight threads**
  - Can a process creation be as cheap as a procedure call?
Definitions

- **Concurrent** process execution can be:
  - interleaved, or
  - physically simultaneous

- **Interleaved**
  - Multi-programming on uniprocessor

- **Physically simultaneous**
  - Uni- or multi-programming on multiprocessor
Definitions...

- **Process, thread, or task**
  - Scheduleable unit of computation

- **Granularity**
  - Process "size" or computation to
  - Communication ratio
    - Too small: excessive overhead
    - Too large: less concurrency
Consider writing a program as a set of tasks.

*Precedence graph:*

specifies execution ordering among tasks

\[
\begin{align*}
S1: & \quad A := X + Y \\
S2: & \quad B := Z + 1 \\
S3: & \quad C := A - B \\
S4: & \quad W := C + 1 \\
\end{align*}
\]

Parallelizing compilers for computers with vector processors build dependency graphs.
What does the following graph represent?

S2 must be performed before S3 begins

AND

S3 must be performed before S2 begins

Precedence Graphs must be ACYCLIC
Let $S_i$ denote a statement.

**Read set of $S_i$:**

$$R(S_i) = \{ a_1, a_2, ..., a_n \}$$

Set of all variables referenced in $S_i$

**Write set of $S_i$:**

$$W(S_i) = \{ b_1, b_2, ..., b_m \}$$

Set of all variables changed by $S_i$
Concurrency Conditions...

C := A - B

R ( C := A - B ) = { A, B }
W ( C := A - B ) = { C }

scanf("%d", &A)

R ( scanf("%d", &A) ) = { }
W ( scanf("%d", &A) ) = { A }
Bernstein's Conditions

The following conditions must hold for two statements S1 and S2 to execute concurrently with valid results:

1) \( R(S1) \text{ INTERSECT } W(S2) = \{ \} \)
2) \( W(S1) \text{ INTERSECT } R(S2) = \{ \} \)
3) \( W(S1) \text{ INTERSECT } W(S2) = \{ \} \)

These are called the Bernstein Conditions.
FORK L
Starts parallel execution at the statement labelled L
and at the statement following the FORK

JOIN Count
Recombines 'Count' concurrent computations

Count := Count - 1;
If
   ( Count > 0 )
Then
   Terminate computation
else continue

Join is an atomic operation.
Structured Parallel Constructs

PARBEGIN / PAREND

PARBEGIN

Sequential execution splits off into several concurrent sequences

PAREND

Parallel computations merge

PARBEGIN

Statement 1;
Statement 2;
...;
Statement N;

PAREND;

PARBEGIN

Q := C mod 25;
Begin

N := N - 1;
T := N / 5;
End;

Proc1 (X, Y);

PAREND;
Parbegin / Parend
Examples

Begin
  PARBEGIN
    A := X + Y;
    B := Z + 1;
  PAREND;
  C := A - B;
  W := C + 1;
End;

Begin
  S1;
  PARBEGIN
    S3;
    BEGIN
      S2;
      S4;
    PARBEGIN
      S5;
      S6;
    PAREND;
  End;
  PAREND;
  S7;
End;
Synchronization with Monitors
Monitors

- P & V are primitive operations
- Semaphore solutions are difficult to accurately express for complex synchronization problems
- Need a High-Level solution: Monitors
- A Monitor is a collection of procedures and shared data
- Mutual Exclusion is enforced at the monitor boundary by the monitor itself
- Data may be global to all procedures in the monitor or local to a particular procedure
- No access of data is allowed from outside the monitor
Condition Variables

- Within the monitor, Condition Variables are declared
- A queue is associated with each condition variable
- Only two operations are allowed on a condition variable:
  
<table>
<thead>
<tr>
<th>X.wait</th>
<th>The procedure performing the wait is put on the queue associated with x</th>
</tr>
</thead>
<tbody>
<tr>
<td>X.signal</td>
<td>If queue is non-empty: resume <em>some</em> process at the point it was made to wait</td>
</tr>
</tbody>
</table>

- Note: V operations on a semaphore are "remembered," but if there are no waiting processes, the signal has no effect
- OS scheduler decides which of several waiting monitor calls to unlock upon signal
Monitor...

- Queue to enter monitor via calls to procedures
- Queues within the monitors via condition variables
- ADTs and condition variables only accessible via monitor procedure calls

```
ADT's condition variables
Proc1
Proc2
Proc3
```

```
queue
```
Monitors contain procedures that control access to a `< CS >`, but not the `< CS >` code itself.

```
Monitor <name>
condition i;

Request

Release

end monitor
```

```
Program

Begin

  Request;

< CS >

  Release;

End;
```
N-Process Critical Section: Monitor Solution

Monitor NCS {
    OK: condition
    Busy: boolean <-- FALSE

    Request() {
        if (Busy) OK.wait;
        Busy = TRUE;
    }
    Release() {
        Busy = FALSE;
        OK.signal;
    }
}

Procedure P {
    NCS.Request();
    <CS>;
    NCS.Release();
}

main() {
    parbegin P;P;P;P; parend }

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monitor sharedBalance {
    int balance;

    public:

    Procedure credit(int amount) {
        balance = balance + amount;
    }

    Procedure debit(int amount) {
        balance = balance - amount;
    }
}
Reader & Writer Schema

```c
reader() {
    while (true) {
        ...
        startRead();
        <read the resource>
        finishRead();
        ...
    }
}

fork(reader, 0);
fork(reader, 0);
fork(writer, 0);

writer() {
    while (true) {
        ...
        startWrite();
        <write resource>
        finishWrite();
        ...
    }
}
```
Reader & Writers Problem: An attempted solution

```java
monitor readerWriter_1{
    int numberOfReaders = 0;
    int numberOfWriters = 0;
    boolean busy = false;

    public:
        startRead()
            while(numberOfReaders != 0);
            numberOfReaders = numberOfReaders+1;
    }
    finishRead() {
        numberOfReaders = numberOfReaders-1;
    }
    startWrite()
        numberOfWriters = numberOfWriters+1;
        while(busy || numberOfReaders > 0);
        busy = true;
    }
    finishWrite() {
        numberOfWriters = numberOfWriters-1;
        busy = false;
    }
}
```

This solution does not work
Reader & Writers Problem:
The solution

```java
monitor reader_writer_2{
    int numberOfReaders = 0;
    boolean busy = false;
    condition okToRead, okToWrite;

    public:
    startRead()
        if (busy || okToWrite.queue) okToRead.wait;
        numberOfReaders = numberOfReaders+1;
        okToRead.signal;
    }
    finishRead() {
        numberOfReaders = numberOfReaders-1;
        if (numberOfReaders =0) okToWrite.signal;
    }
    startWrite()
        if (busy || numberOfReaders != 0) okToWrite.wait;
        busy = true;
    }
    finishWrite() {
        busy = false;
        if (okToWrite.queue) okToWrite.signal;
        else okToRead.signal;
    }
}
```
Dining Philosophers’ Problem:
The solution

```cpp
enum status {eating, hungry, thinking};
monitor diningPhilosophers{
    status state[N]; condition self[N]; int j;
    // This procedure can only be called from within the monitor
    test(int i) {
        if((state[i=1 MOD N] != eating) && (state[i] == hungry)
            && (state[i+1 MOD N] != eating) ) {
            state[i] = eating;
            self[i].signal;
        }
    }
    public:
    pickUpForks(){
        state[i] = hungry;
        test(i);
        if(state[i] != eating) self[i].wait;
    }
putDownForks(){
        state[i] = thinking;
        test(i-1 MOD N); test(i+1 MOD N);
    }
diningPhilosophers() { // Monitor initialization code
    for(int i=0; i<N; i++) state[i] = thinking;
    }
}
```
Simple Resource Allocation with a monitor

```pascal
monitor resourceAllocator;
var resourceInUse: boolean;
    resourceIsFree: condition;

procedure getResource;
begin
    if(resourceInUse) wait(resourceIsFree);
    resourceInUse := true;
end;

procedure returnResource;
begin
    resourceInUse := false;
    signal(resourceIsFree);
end;
begin
    resourceInUse := false;
end.
```

Can use as a Semaphore
Monitor implementation of a ring buffer

```pascal
monitor ringBufferMonitor;

var ringBuffer: array[0..slots-1] of stuff;
    slotInUse: 0..slots;
    nextSlotToFill: 0..slots-1;
    nextSlotToEmpty: 0..slots-1;
    ringBufferHasData, ringBufferHasSpace: condition;

procedure fillASlot(slotData: stuff);
begin
    if (slotInUse = slots) then wait(ringBufferHasSpace);
    ringBuffer[nextSlotToFill] := slotData;
    slotInUse := slotInUse + 1;
    nextSlotToFill := (nextSlotToFill+1) MOD slots;
    signal(ringBufferHasData);
end;
```
Monitor implementation of a ring buffer...

```pascal
procedure emptyASlot(var slotData: stuff);
begin
  if (slotInUse = 0) then wait(ringBufferHasData);
  slotData := ringBuffer[nextSlotToEmpty];
  slotInUse := slotInUse - 1;
  nextSlotToEmpty := (nextSlotToEmpty-1) MOD slots;
  signal(ringBufferSpace);
end;

begin
  slotInUse := 0;
  nextSlotToFill := 0;
  nextSlotToEmpty := 0;
end.
```