Chapter 9

# High-level Synchronization

# Introduction to Concurrency

- **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: | Program Style: |
|---|---|
| Uniprocessor with:<br>- I/O channel<br>- I/O processor<br>- DMA | Multiprogramming,<br>multiple process system<br>programs |
| Multiprocessor | Parallel programming |
| Network of processors | Distributed Programs |

# 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

- **<u>Concurrent</u>** process execution can be:
  - interleaved, or
  - physically simultaneous

- <u>Interleaved</u>
  - <u>Multi-programming</u> on uniprocessor

- <u>Physically simultaneous</u>
  - Uni- or multi-programming on <u>multiprocessor</u>

# 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

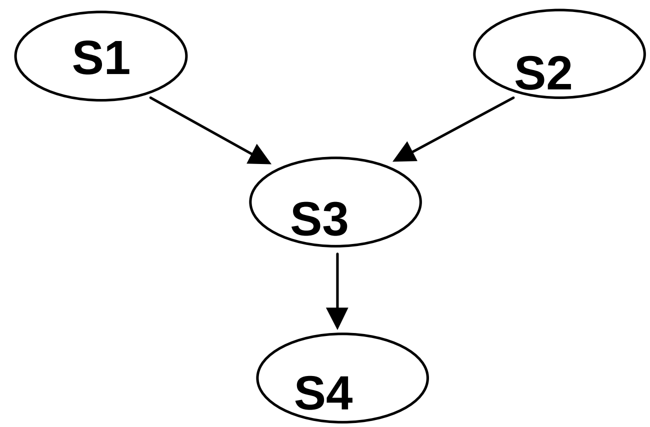
# Precedence Graph

Consider writing a program as a set of tasks.

*<u>Precedence graph:</u>*

specifies execution ordering among tasks

```
S1:    A := X + Y
S2:    B := Z + 1
S3:    C := A - B
S4:    W := C + 1
```




Parallelizing compilers for computers with vector processors build dependency graphs.

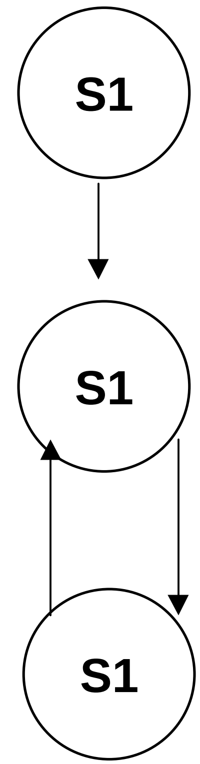
# Cyclic Precedence Graph

**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**

# Concurrency Conditions

Let ***Si*** denote a statement.

**Read set of Si:**

R (Si) = { a1, a2, ..., an }

Set of all variables referenced in Si

**Write set of Si:**

W (Si) = { b1, b2, ..., bm },

Set of all variables changed by Si

# 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 ) INTERSECT W ( S2 ) = { }
2) W ( S1 ) INTERSECT R ( S2 ) = { }
3) W ( S1 ) INTERSECT W ( S2 ) = { }

These are called the **Bernstein Conditions.**

# Parallel Language Constructs (Review)

**FORK and JOIN**

**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;
    PARBEND;
    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

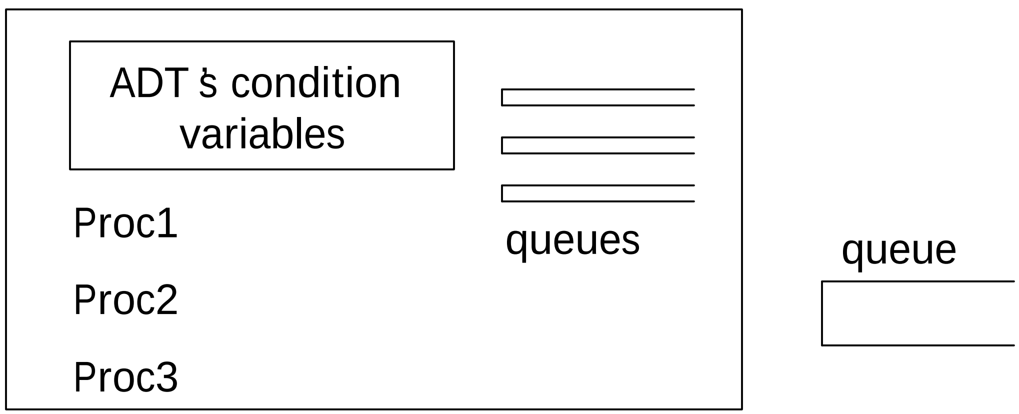
- Within the monitor, Condition Variables are declared
- A queue is associated with each condition variable
- Only two operations are allowed on a condition variable:

| | |
|---|---|
| **X.wait** | The procedure performing the wait is put on the queue associated with x |
| **X.signal** | If queue is non-empty: resume *some* process at the point it was made to wait |

- 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



# Monitors...

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 }
```

# Shared Variable Monitor

```
monitor sharedBalance {
        int balance;
public:
        Procedure credit(int amount)
                { balance = balance + amount;}
        Procedure debit(int amount)
                { balance = balance - amount;}
}
```

# Reader & Writer Schema

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

```
writer() {
   while(true){
        ...
        startWrite();
        <write resource>
        finishWrite();
        ...
    }
}
```

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

# Reader & Writers Problem:
## An attempted solution

```
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

```
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

```
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

```
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

```
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...

```
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.
```