# CSCI 8220 Parallel and Distributed Simulation

**PDES Introduction**

**The Null Message Synchronization Algorithm**



# Outline

- Parallel / Distributed Computers
- Air Traffic Network Example
- Parallel Discrete Event Simulation
  - » Logical processes & time stamped messages
  - » Local causality constraint and the synchronization problem
- Chandy/Misra/Bryant Null Message Algorithm
  - » Ground rules
  - » An algorithm that doesn't work
  - » Deadlock avoidance using null messages



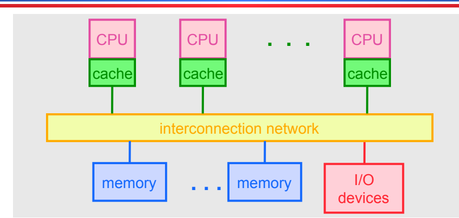
# Parallel and Distributed Computers

- Parallel computers (tightly coupled processors)
  - » Shared memory multiprocessors
  - » Distributed memory multicomputers
- Distributed computers (loosely coupled processors)
  - » Networked workstations

| | Parallel Computers | Distributed Computers |
|---|---|---|
| **Physical extent** | Machine room | Building, city, global |
| **Processors** | Homogeneous | Often heterogeneous |
| **Comm. Network** | Custom switch | Commercial LAN / WAN |
| **Comm. Latency (small messages)** | A few to tens of microseconds | hundreds of microseconds to seconds |



# Shared Memory Multiprocessors



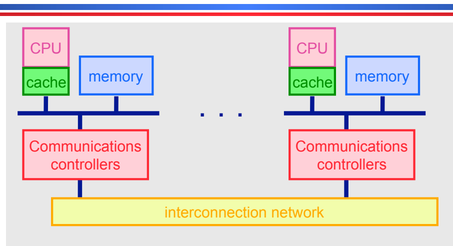

Examples:
Sun Enterprises
SGI Origin

*programming model:* shared variables; synchronization via `locks`

| Processor 1 | Processor 2 |
|---|---|
| `{ shared int i; L … Lock( L ) i = i + 1; Unlock( L ) … }` | `{ shared int i; L … Lock( L ) i = i + 1; Unlock( L ) … }` |



# Distributed Memory Multiprocessors

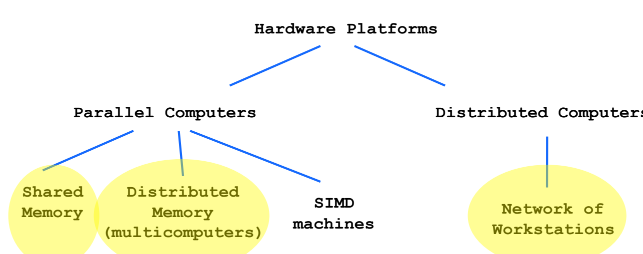



Examples:
IBM SP
Intel Paragon

*programming model:* no shared variables: message passing

| Processor 1 | Processor 2 |
|---|---|
| `{ int i; … Send( 2, &i, sizeof(int)) … }` | `{ int j; … Receive( &j, sizeof(int)) … }` |





# Event-Oriented World View

Simulation application

state variables

```
Integer: InTheAir;
Integer: OnTheGround;
Boolean: RunwayFree;
```

Event handler procedures

```
Arrival Event        Landed Event        Departure Event
{                    {                   {
  …                    …                   …
}                    }                   }
```

Simulation executive

Now = 8:45

Pending Event List (PEL): 9:00, 9:16, 10:10

Event processing loop

```
while(simulation not finished)
  E = smallest time stamp event in PEL
  Remove E from PEL
  Now := time stamp of E
  call event handler procedure
```



# Parallel Discrete Event Simulation

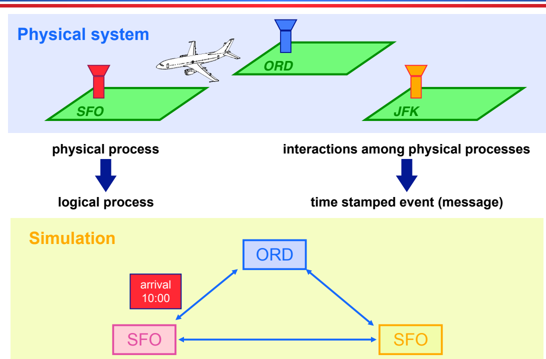
- **Extends** example to model a network of airports
  - » **Encapsulate** each airport simulator in a **logical process**
  - » Logical processes can schedule events (**send messages**) for other logical processes

**More generally...**

- **Physical system**
  - » Collection of interacting physical processes (airports)
- **Simulation**
  - » Collection of logical processes (LPs)
  - » Each LP models a physical process
  - » **Interactions** between physical processes modeled by scheduling events between LPs



# Parallel Discrete Event Simulation: Example




*all interactions between LPs must be via messages (no shared state)*



# LP Simulation Example

`Now`: current simulation time
`InTheAir`: number of aircraft landing or waiting to land
`OnTheGround`: number of landed aircraft
`RunwayFree`: Boolean, true if runway available

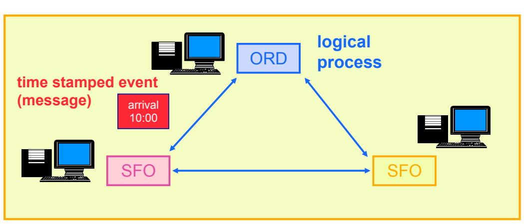
```
Arrival Event:
    InTheAir := InTheAir+1;
    if( RunwayFree )
      RunwayFree:=FALSE;
      Schedule Landed event(local) @ Now + R;

Landed Event:
    InTheAir := InTheAir-1;
    OnTheGround := OnTheGround + 1;
    Schedule Departure event(local) @ Now + G;
    if( InTheAir > 0 ) Schedule Landed event(local) @ Now + R;
    else RunwayFree := True;
Departure Event: (D = Delay to reach another airport)
    OnTheGround := OnTheGround - 1;
    Schedule Arrival Event (remote) @ (Now+D) @ another airport
```



# Parallel Discrete Event Simulation: Example

- LP paradigm appears well suited to concurrent execution
- Map LPs to different processors
  - » Multiple LPs per processor OK
- Communication via message passing
  - » All interactions via messages
  - » No shared state variables





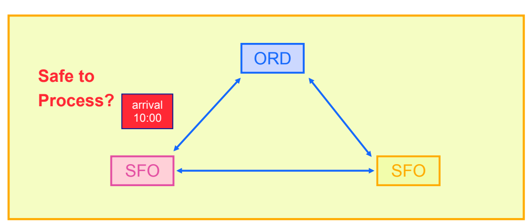

# The "Rub"

Golden rule

**Golden rule for each process:**

**"Thou shalt process incoming messages in time stamp order"**

**local causality constraint**



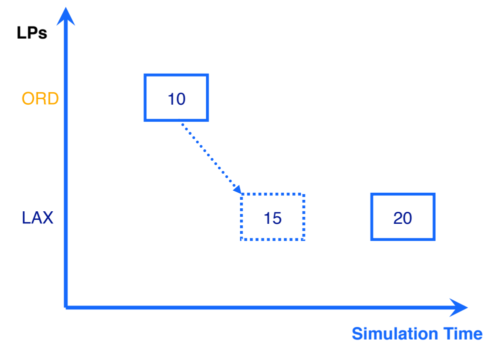
## The Synchronization Problem

**Synchronization Problem**: An algorithm is needed to ensure each LP processes events in time stamp order

**Observation**: Ignoring events with the same time stamp (for now), adherence to the local causality constraint is sufficient to ensure that the parallel simulation **will produce exactly the same results as a sequential execution** where all events across all LPs are processed in time stamp order.



## The Synchronization Problem






## Synchronization Algorithms

- **Conservative synchronization**: avoid violating the local causality constraint (wait until it's safe)
  - » deadlock avoidance using null messages (Chandy/Misra/Bryant)
  - » deadlock detection and recovery
  - » synchronous algorithms (e.g., execute in "rounds")
- **Optimistic synchronization**: allow violations of local causality to occur, but detect them at runtime and recover using a rollback mechanism
  - » Time Warp (Jefferson)
  - » numerous other approaches



## Outline

- Parallel / Distributed Computers
- Air Traffic Network Example
- Parallel Discrete Event Simulation
  - » Logical processes
  - » Local causality constraint
- Chandy/Misra/Bryant Null Message Algorithm
  - » Ground rules
  - » An algorithm that doesn't work
  - » Deadlock avoidance using null messages

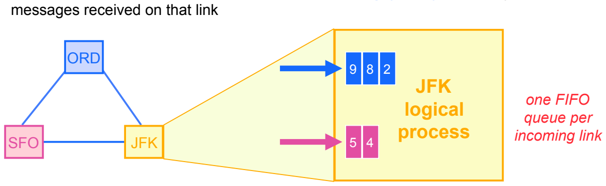


## Conservative Algorithms

**Assumptions:**

- logical processes (LPs) exchanging time stamped events (messages)
- static network topology, no dynamic creation of LPs
- messages sent on each link are sent in time stamp order
- network provides reliable delivery, preserves order

**Observation:** The above assumptions imply the time stamp of the last message received on a link is a lower bound on the time stamp (LBTS) of subsequent messages received on that link



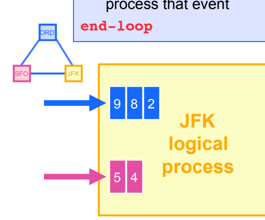

**Goal:** Ensure LP processes events in time stamp order



## A Simple Conservative Algorithm

**Algorithm A** (executed by each LP):
**Goal: Ensure events are processed in time stamp order:**

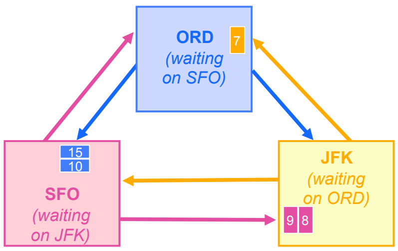
```
while( simulation is not over )
    wait until each FIFO contains at least one message
    remove smallest time stamped event from its FIFO
    process that event
end-loop
```




- process time stamp 2 event
- process time stamp 4 event
- process time stamp 5 event
- wait (block ) until message is received from SFO

*Observation: Algorithm A is prone to deadlock! (cycle of empty queues…)*

# Deadlock Example

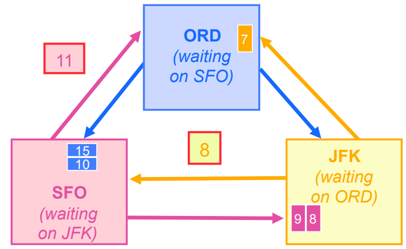



*A cycle of LPs forms where each is waiting on the next LP in the cycle.*
*No LP can advance; the simulation is deadlocked.*



# Deadlock Avoidance Using Null Messages

*Break deadlock: each LP send "null" messages indicating a lower bound on the time stamp of future messages.*




**Assume minimum delay (flight time) between airports is 3 units of time**

- JFK initially at time 5
- JFK sends null message to SFO with time stamp **8 = (5 +3)**
- SFO sends null message to ORD with time stamp **11 = (8+3)**
- ORD may now process message with time stamp **7**

# Deadlock Avoidance Using *Null* Messages

**Null Message Algorithm** (executed by each LP):
**Goal**: Ensure events are processed in time stamp order and avoid deadlock

```
while( simulation is not over )
    wait until each FIFO contains at least one message
    remove smallest time stamped event from its FIFO
    process that event
    send null messages to neighboring LPs with time stamp indicating a
        lower bound on future messages sent to that LP (current time plus
        lookahead )
end-loop
```

*The null message algorithm relies on a "lookahead" ability.*

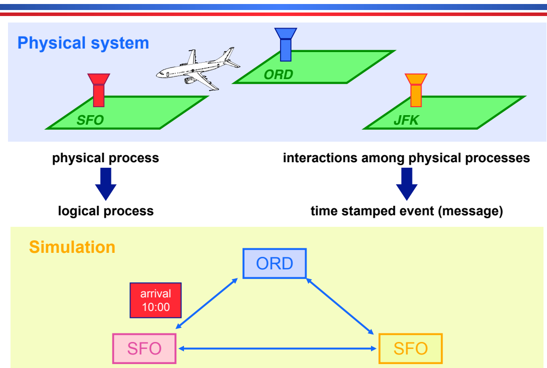


# Summary

- **Parallel Discrete Event Simulation**
  - » **Collection of sequential simulators (LPs) possibly running on different processors**
  - » **Logical processes communicating exclusively by exchanging messages**
- **Chandy/Misra/Bryant Null Message Algorithm**
  - » **Null messages: Lower bound on the time stamp of future messages the LP will send**
  - » **Null messages avoid deadlock (non-zero lookahead)**



# Parallel Discrete Event Simulation: Example




*all interactions between LPs must be via messages (no shared state)*