• **physical system**: the actual or imagined system being modeled
• **simulation**: a system that emulates the behavior of a physical system

### Time

- **physical time**: time in the physical system
  - Noon, December 31, 1999 to noon January 1, 2000

- **simulation time**: representation of physical time within the simulation
  - floating point values in interval [0.0, 24.0]

- **wallclock time**: time during the execution of the simulation, usually output from a hardware clock
  - 9:00 to 9:15 AM on September 10, 1999
Simulation Time

Simulation time is defined as a totally ordered set of values where each value represents an instant of time in the physical system being modeled.

For any two values of simulation time $T_1$ representing instant $P_1$, and $T_2$ representing $P_2$:

- **Correct ordering of time instants**
  - If $T_1 < T_2$, then $P_1$ occurs before $P_2$
  - 9.0 represents 9 PM, 10.5 represents 10:30 PM

- **Correct representation of time durations**
  - $T_2 - T_1 = k (P_2 - P_1)$ for some constant $k$
  - 1.0 in simulation time represents 1 hour of physical time
Paced vs. Unpaced Execution

Modes of execution

- **As-fast-as-possible** execution (unpaced): no fixed relationship necessarily exists between advances in simulation time and advances in wallclock time.

- **Real-time** execution (paced): each advance in simulation time is paced to occur in synchrony with an equivalent advance in wallclock time.

- **Scaled real-time** execution (paced): each advance in simulation time is paced to occur in synchrony with $S \times$ an equivalent advance in wallclock time (e.g., 2x wallclock time).

Simulation Time $= W2S(W) = T_0 + S \times (W - W_0)$

$W =$ wallclock time; $S =$ scale factor

$W_0$ ($T_0$) = wallclock (simulation) time at start of simulation (assume simulation and wallclock time use same time units)
Discrete Event Simulation

Discrete event simulation: computer model for a system where changes in the state of the system occur at discrete points in simulation time.

Fundamental concepts:
• system state (state variables)
• state transitions (events)

A DES computation can be viewed as a sequence of event computations, with each event computation is assigned a (simulation time) time stamp

Each event computation can
• modify state variables
• schedule new events
Discrete Event Simulation Computation

example: air traffic at an airport
events: aircraft arrival, landing, departure

- Unprocessed events are stored in a pending event list
- Events are processed in time stamp order
Discrete Event Simulation System

model of the physical system

independent of the simulation application

Simulation Application
- state variables
- code modeling system behavior
- I/O and user interface software

Simulation Executive
- event list management
- managing advances in simulation time

calls to schedule events

calls to event handlers
**Event-Oriented World View**

**State Variables**
- Integer: InTheAir;
- Integer: OnTheGround;
- Boolean: RunwayFree;

**Event Handler Procedures**

<table>
<thead>
<tr>
<th>Event</th>
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<tbody>
<tr>
<td>Arrival</td>
<td>Landed</td>
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**Simulation Application**

**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
```
Example: Air traffic at an Airport

Model aircraft arrivals and departures, arrival queueing
Single runway for incoming aircraft, ignore departure queueing

- \( R \) = time runway is used for each landing aircraft (constant)
- \( G \) = time required on the ground before departing (constant)

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

Events:
- **Arrival**: denotes aircraft arriving in air space of airport
- **Landed**: denotes aircraft landing
- **Departure**: denotes aircraft leaving
Arrival Events

New aircraft arrives at airport. If the runway is free, it will begin to land. Otherwise, the aircraft must circle, and wait to land.

- $R =$ time runway is used for each landing aircraft
- $G =$ time required on the ground before departing
- $\text{Now}: \text{ current simulation time}$
- $\text{InTheAir}: \text{ number of aircraft landing or waiting to land}$
- $\text{OnTheGround}: \text{ number of landed aircraft}$
- $\text{RunwayFree}: \text{ Boolean, true if runway available}$

Arrival Event:

$\text{InTheAir} := \text{InTheAir}+1$;

If (RunwayFree)

$\text{RunwayFree} := \text{FALSE};$

Schedule Landed event $\text{@ Now + R;}$
Landed Event

An aircraft has completed its landing.

- \( R \) = time runway is used for each landing aircraft
- \( G \) = time required on the ground before departing
- \( \text{Now} \): current simulation time
- \( \text{InTheAir} \): number of aircraft landing or waiting to land
- \( \text{OnTheGround} \): number of landed aircraft
- \( \text{RunwayFree} \): Boolean, true if runway available

Landed Event:

\[
\text{InTheAir} := \text{InTheAir} - 1;
\]
\[
\text{OnTheGround} := \text{OnTheGround} + 1;
\]

Schedule Departure event @ Now + G;

If (InTheAir > 0)

- Schedule Landed event @ Now + R;

Else

- RunwayFree := TRUE;
Departure Event

An aircraft now on the ground departs for a new destination.

- R = time runway is used for each landing aircraft
- G = time required on the ground before departing
- Now: current simulation time
- InTheAir: number of aircraft landing or waiting to land
- OnTheGround: number of landed aircraft
- RunwayFree: Boolean, true if runway available

Departure Event:
OnTheGround := OnTheGround - 1;
Simulation Time

State Variables

InTheAir

OnTheGround

RunwayFree

time

Processing:

Time Event
1 Arrival F1
3 Arrival F2
4 Landed F1
7 Landed F2
8 Depart F1
11 Depart F2

Time Event
3 Arrival F2
4 Landed F1
7 Landed F2
11 Depart F1
11 Depart F2

Now=0
Now=1
Now=3
Now=4
Now=7
Now=8
Now=11

R=3
G=4
false
true
true
false
true
false
true
false
true
false
true
Summary

- **Time**
  - Important to distinguish among simulation time, wallclock time, and time in the physical system
  - Paced execution (e.g., immersive virtual environments) vs. unpaced execution (e.g., simulations to analyze systems)

- **DES computation**: sequence of event computations
  - Modify state variables
  - Schedule new events

- **DES System = model + simulation executive**

- **Data structures**
  - Pending event list to hold unprocessed events
  - State variables
  - Simulation time clock variable

- **Program (Code)**
  - Main event processing loop
  - Event procedures
  - Events processed in time stamp order