CSCI: 4210/6210
Simulation & Modeling

Event-Oriented Simulations

Outline

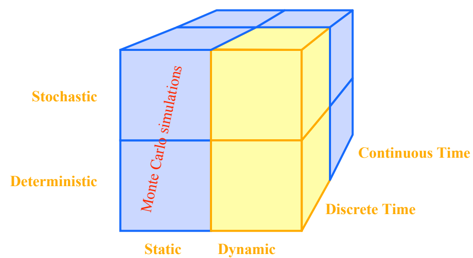
- Simulation modeling characteristics
- Concept of Time
- A DES computation
- DES System = model + simulation executive
- Data structures
- Program (Code)

Simulation Model Characteristics

Today we will look at:

- Static or dynamic models
- Stochastic, deterministic or chaotic models
- Discrete or continuous change/models
- Aggregates or Individuals

Computer Art: Brownian Tree - fractal with a dendritic structure. Generated stochastically



Static or Dynamic Models

- **Dynamic**:
  - » State variables change over time
  - » System Dynamics, Discrete Event, Agent-Based
- **Static**:
  - » Snapshot at a single point in time
  - » Monte Carlo simulation, optimization models

	Inputs							Response
Repetitions	$X_{i,1}$	$X_{i,2}$	$X_{i,3}$	…	$X_{i,j}$	…	$X_{i,p}$	y_i
1								
2								
3								
.								
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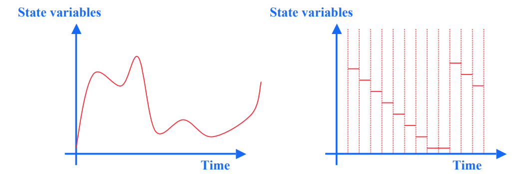
Deterministic, Stochastic or Chaotic

- **Deterministic**:
  - » Predictive behavior. The system is perfectly understood, then it is possible to predict precisely what will happen.
  - » Repeatable
- **Stochastic**:
  - » behavior cannot be entirely predicted.
- **Chaotic**:
  - » deterministic model with a behavior that cannot be entirely predicted. Depends so sensitively on the system's initial conditions so that in effect it cannot be predicted.

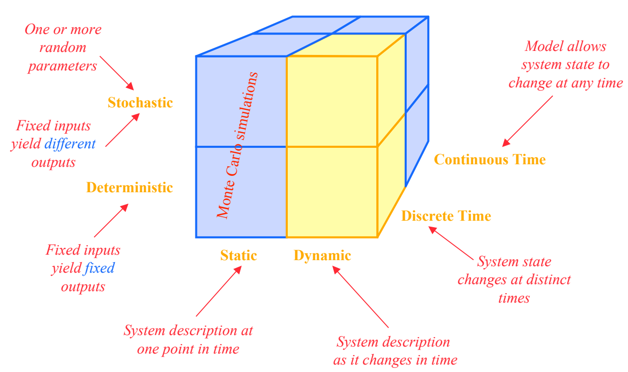
Discrete or Continuous Models

- **Discrete model**:
  - » **state variables change only at a countable number of points in time.**
    - – **These points in time are the ones at which the event occurs/change in state.**
- **Continuous model**:
  - » **state variables change in a continuous way, and not abruptly from one state to another.**
  - » **infinite number of states.**

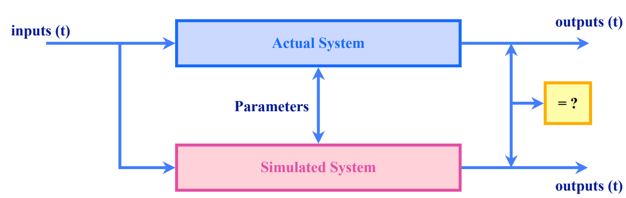


Continuous: State variables change continuously as a function of time
State variables = *f(t)*

Discrete: State variables change at discrete times

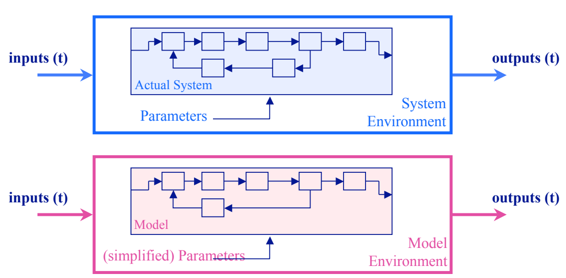


Simulation



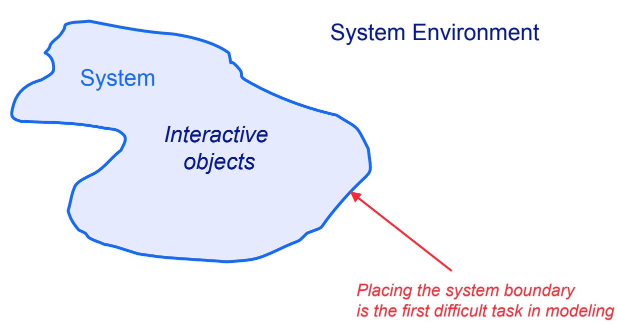
- **Simulated system imitates operations of actual system over time**
- **Artificial history of system can be generated and observed**
- **Internal (perhaps unobservable) behavior of system can be studied**
- **Time scale can be altered as needed**
- **Conclusion about actual system characteristics can be inferred**

What is a Simulation Model?

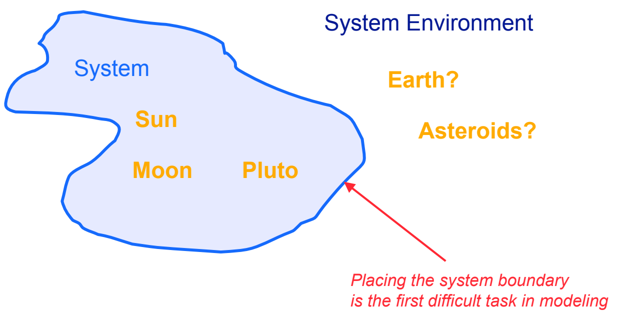


- **An abstraction of a real system**
- **Simplified assumptions are used to capture (only) important behaviors**

System's Modeling



System's Modeling

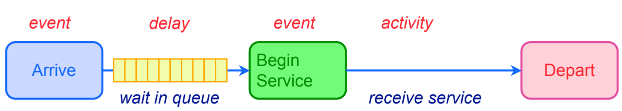


Entities, Attributes and Activities...

- An entity is an object of interest in the system
  - » Example: Customer Manager Cashier
- An attribute is a (relevant) property of an entity
  - » Example: Account balance Gender Skills
- Attributes are state variables

Activities & Delays

- An activity… … is a duration of a known length
  - » Example: drink coffee, serve customers
  - » Activities form part of the model specification
  - » Inter-arrival time, service time
  - » Deterministic or stochastic (probabilistic)
- A delay… … is a duration of unknown length
  - » waiting time in queue
- Delays form part of the simulation results
  - » Example: waiting time in queue
  - » Delays form part of the simulation results



State and State Variables

- The (system) state
  - » complete
  - » minimal
  - » contains sufficient information to describe the system at any point in time.
- A state variable
  - » Describes a portion of the state.
  - » Length of a queue, activity of a manager (sleeping, drinking coffee)

Events

- Event:
  - » Occurrence
  - » Instantaneous
  - » May change the state
- Example single server queue:
  - » Arrival -- while the server is busy, so queue length is incremented by 1;
  - » Departure -- the completion of service

Conditional and Primary Events

- Primary Events
  - » Scheduled at a certain time
  - » Arrival of customers
- Conditional Events
  - » triggered by a certain condition becoming TRUE -- a completion of a delay
  - » Customers moving from queue to service

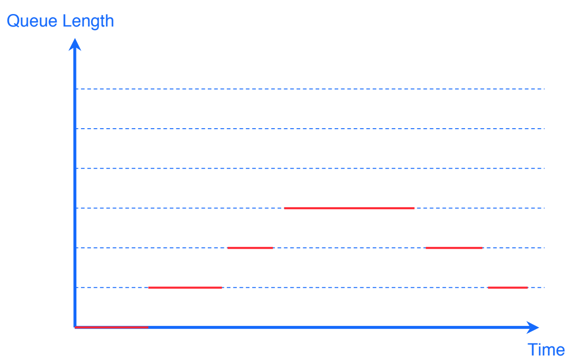
How to Create a DES?

- DES Modeling raises the following questions?
  - How does each event affect system state and attributes?
  - How are activities defined?
    - What events mark beginning and the end?
    - What condition (if any) most hold?
  - How are delays defined?
  - How is the simulation initialized?

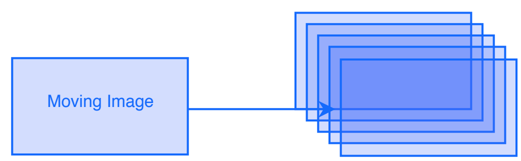
A Simulation Example

- Single-server Queue at a bank
- One possible problem formulation:
  - "customer have to wait too long in my bank"
- Objective:
  - Determine the effect of an additional cashier
- Data needed:
  - inter-arrival time of customers
  - Service times

Simulation Results

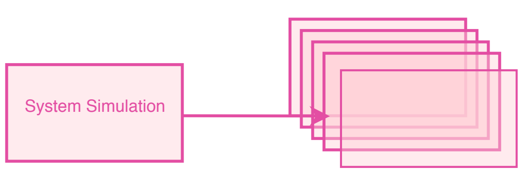


Movie



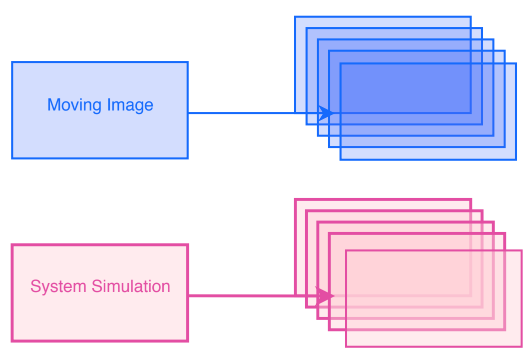
- Series of still images, sufficient to convey recognizable motion

System Snapshots



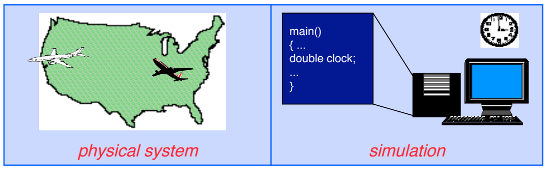
- Series of system snapshot
  - system state
  - activities in progress
  - end time

System Snapshots



Time

- ***Physical system:*** actual or imagined system being modeled
- ***Simulation***: a system that emulates the behavior of a physical system



- **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**

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 * an equivalent advance in wallclock time (e.g., 2 x wallclock time)

Converting from wallclock to Simulation Time:

Simulation Time = W2S(W) = T_0 + S * (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)**

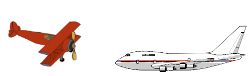
A DES computation: can be viewed as a *sequence of event computations,* with each event computation is assigned a (simulation time) time stamp. Each event computation can

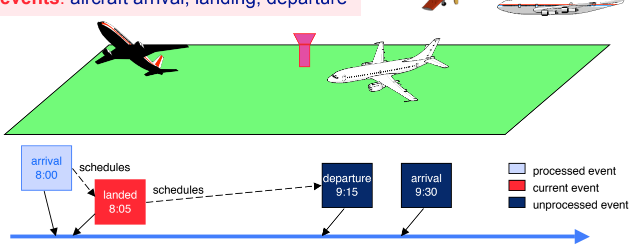
- **modify state variables**
- **schedule new events**

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

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

calls to schedule events ↓ ↑ calls to event handlers

Independent of the simulation application

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

Event-Oriented World View

state variables

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

Event handler procedures

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

Simulation application

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
```


Example: Air traffic at an Airport

Model aircraft arrivals and departures, arrival queuing

Single runway for incoming aircraft, ignore departure queuing

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

```
Landed Event:
    InTheAir := InTheAir-1;
    OnTheGround := OnTheGround + 1;
    Schedule Departure event @ Now + G;
    if( InTheAir > 0 )
      Schedule Landed event @ Now + R;
    else
      RunwayFree := True;
```

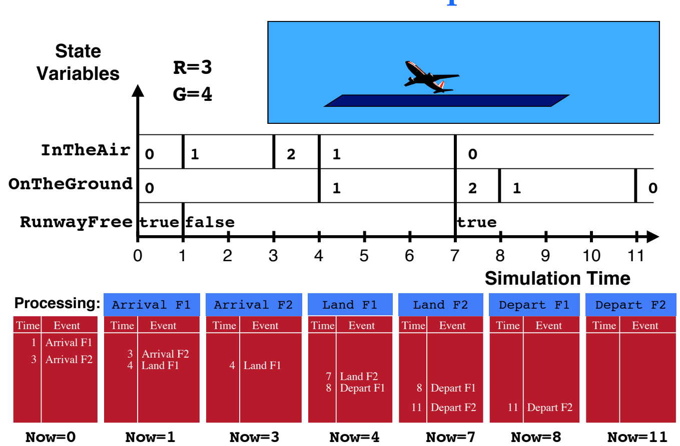

Departure Event

An aircraft 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;
```


Execution Example



Summary

- Simulation modeling characteristics
- 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