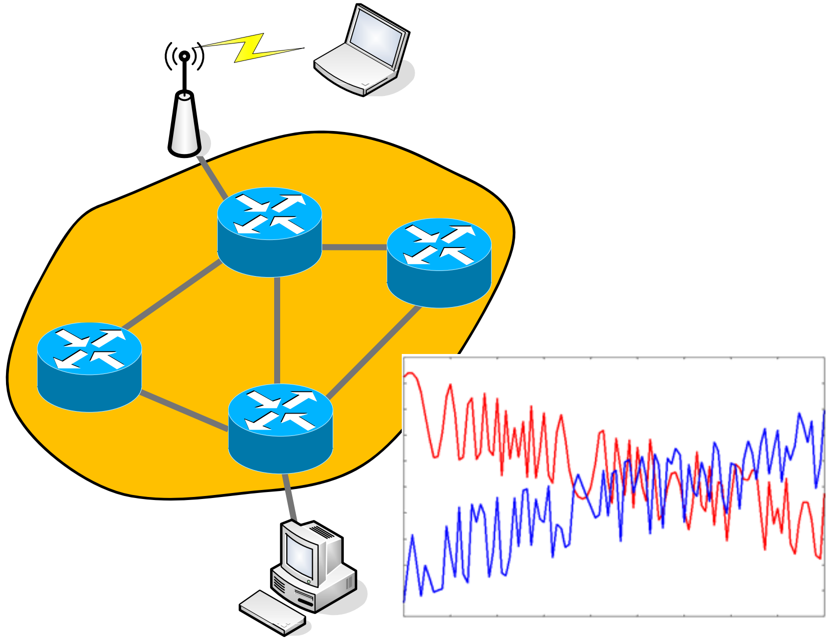
# Chapter 3

## General Principles



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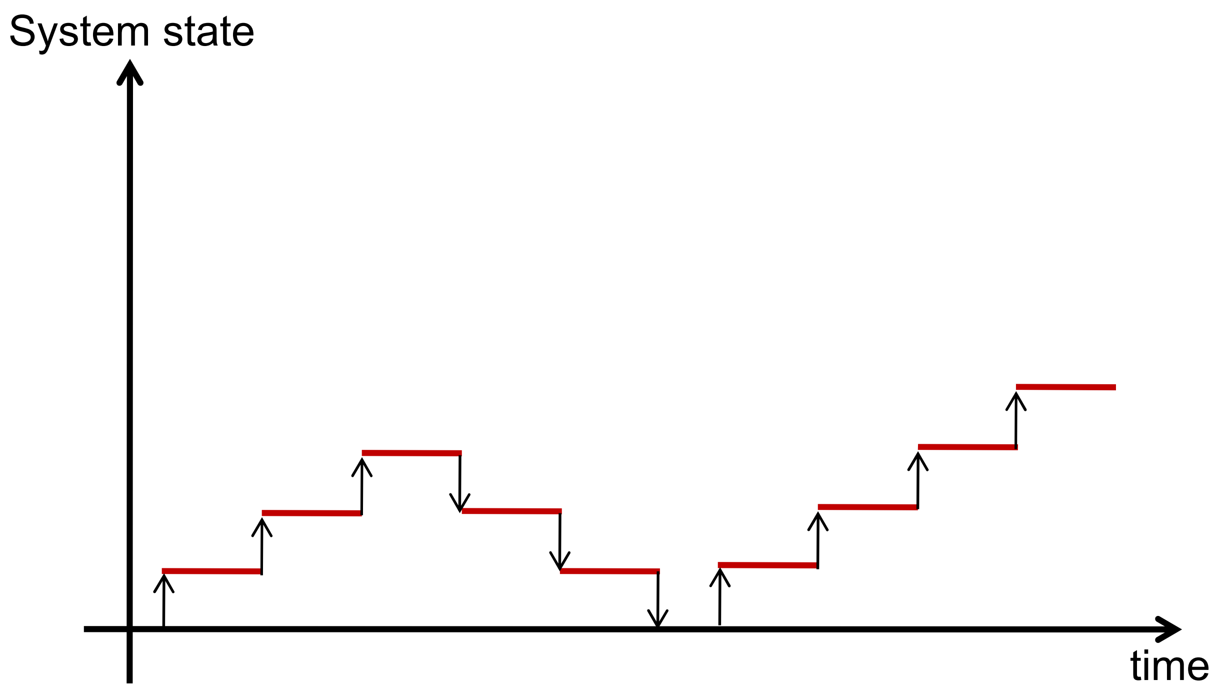
- Concepts of Discrete-Event Simulation
- The Event Scheduling / Time Advance Algorithm
- World Views
- Manual Simulation using Event Scheduling
- Simulation in Java
- Object-oriented Simulation Framework in Java
- Modeling of Discrete-Event Simulations

# Concepts of Discrete-Event Simulation

# General Principles: Introduction

- Framework for modeling systems by discrete-event simulation
  - A system is modeled in terms of its state at each point in time
  - This is appropriate for systems where changes occur only at discrete points in time



# Concepts in Discrete-Event Simulation

- Concepts of dynamic, stochastic systems that change in a discrete manner

| | |
|---|---|
| System | A **collection of entities** that interact together over time to accomplish one or more goals, e.g., bank, production system, computer system, network. |
| Model | An **abstract representation** of a system, usually containing structural, logical, or mathematical relationships that describe the system. |
| System state | A **collection of variables** that contain all the information necessary to describe the system at any time. |
| Entity | An **object** in the system that **requires explicit representation** in the model, e.g., people, machines, nodes, packets, server, customer. |
| Attributes | The **properties of** a given **entity**, e.g., length of a packet, capacity of a machine. |
| List, Set | A **collection of** associated **entities** ordered in some logical fashion in a waiting line.<br>▪ Holds entities and event notices.<br>▪ Entities on a list are always ordered by some rule, e.g., FIFO, LIFO, or ranked by some attribute, e.g., priority, due date. |
| Event | An **instantaneous occurrence** that changes the state of a system. |
| Event notice | A **record of an event to occur** at the current or some future time, along with any associated data necessary to execute the event. |

# Concepts in Discrete-Event Simulation

| | |
|---|---|
| Event list | A **list of event notices** for future events, ordered by time of occurrence; known as the future event list (FEL) or future event set (FES).<br>▪ Always **ranked** by the **event time.** |
| Activity | A **duration of** time of **specified length**, which is known when it begins.<br>▪ Represents a service time, interarrival time, or any other processing time whose duration has been characterized by the modeler. The duration of an activity can be specified as:<br>• Deterministic: Always 5 time units<br>• Statistical: Random draw from {2, 5, 7}<br>• A function: Depending on system variables and entities<br>▪ The **duration** of an activity **is computable when it begins**<br>▪ The duration is **not affected** by **other events**<br>▪ To **track activities**, an event notice is created for the completion time, e.g., let clock=100 and service with duration 5 time units is starting<br>• Schedule an "end of service"-event for clock + 5 = 105 |
| Delay | A **duration of** time of **unspecified** indefinite **length**, which is not known until it ends.<br>▪ Customer's delay in waiting line depends on the number and service times of other customers.<br>▪ Typically a desired output of the simulation run. |
| Clock | A variable representing the simulated time. |

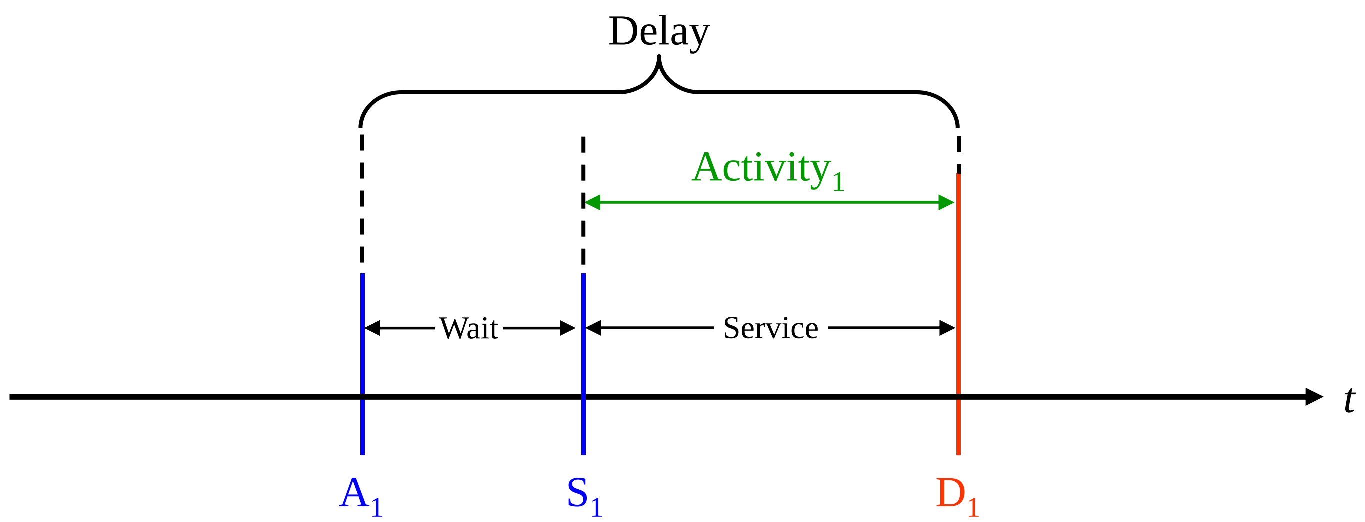
# Concepts in Discrete-Event Simulation

## Activity vs. Delay

- Activity
  - Activity is known as unconditional wait
  - End of an activity is an event, for this an event notice is placed in the future event list
  - This event is a primary event
- Delay
  - Delay is known as conditional wait
  - Delays are managed by placing the entity on another list, e.g., representing a waiting line
  - Completion of delay is a secondary event, but they are not placed in the future event list

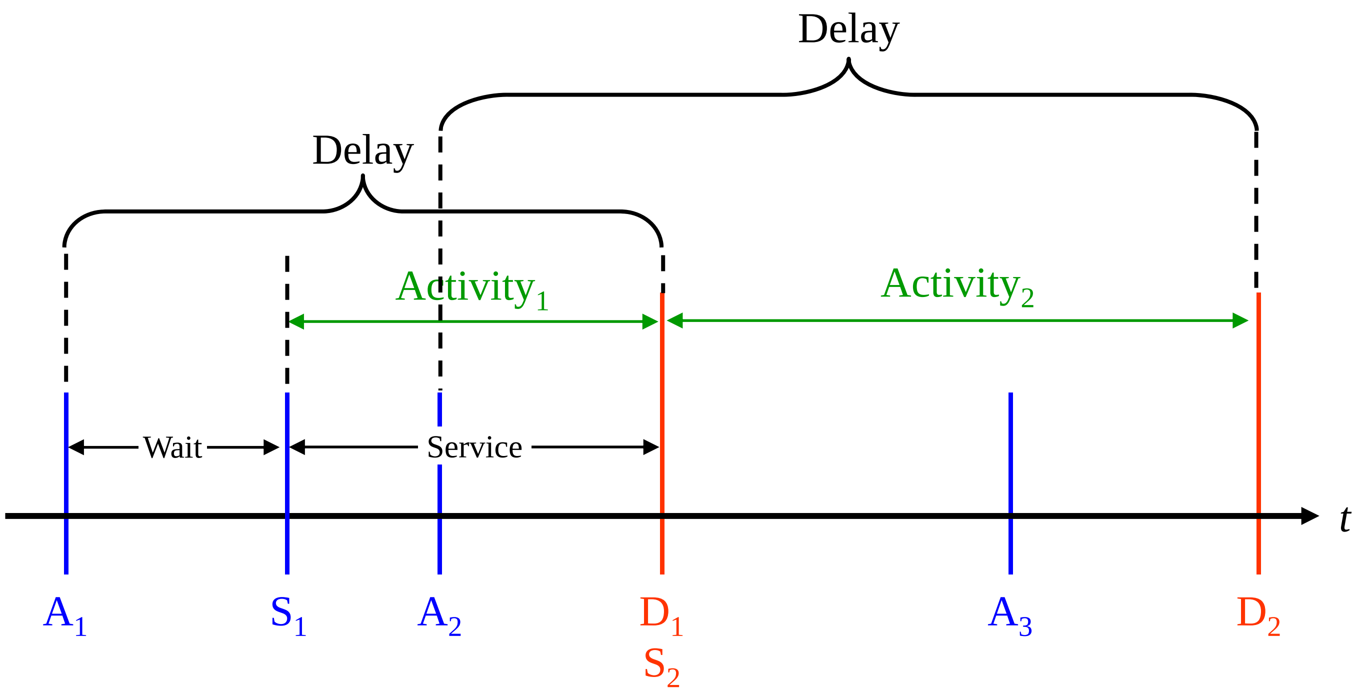
# Concepts in Discrete-Event Simulation

- Activity vs. Delay



# Concepts in Discrete-Event Simulation

- Activity vs. Delay



# Concepts in Discrete-Event Simulation

- Activity vs. Delay

# Concepts in Discrete-Event Simulation: Example

Consider Call Center Example from Chapter 2

- System state at time $t$ is given by $[\mathrm{LQ}(t), \mathrm{LA}(t), \mathrm{LB}(t)]$
  - $\mathrm{L_Q}(t)$: Number of callers waiting to be served at time $t$
  - $\mathrm{L_A}(t)$: 0 or 1 to indicate Able as being idle or busy at time $t$
  - $\mathrm{L_B}(t)$: 0 or 1 to indicate Baker as being idle or busy at time $t$
- Entities
  - Neither callers nor the servers are explicitly represented
- Events
  - Arrival event
  - Service completion by Able
  - Service completion by Baker
- Activities
  - Interarrival time of callers
  - Service time by Able
  - Service time by Baker
- Delay
  - A caller‘s waiting time in queue until Able or Baker becomes free

# Concepts in Discrete-Event Simulation

- A model consists of
  - static description of the model and
  - the dynamic relationships and interactions between the components

- Some questions that need to be answered for the dynamic behavior
  - Events
    - How does each event affect system state, entity attributes, and set contents?
  - Activities
    - How are activities defined?
    - What event marks the beginning or end of each activity?
    - Can the activity begin regardless of system state, or is its beginning conditioned on the system being in a certain state?
  - Delays
    - Which events trigger the beginning (and end) of each delay?
    - Under what condition does a delay begin or end?
  - System state initialization
    - What is the system state at time 0?
    - What events should be generated at time 0 to “prime” the model – that is, to get the simulation started?

# Concepts in Discrete-Event Simulation

- A discrete-event simulation proceeds by producing a sequence of system snapshots over time
- A snapshot of the system at a given time includes
  - System state
  - Status of all entities
  - Status of all sets
    - Sets are used to collect required information for calculating performance metrics
  - Future event list (FEL)
  - Statistics

| Clock | System state | Entities and attributes | Set 1 | Set 2 | ... | Future event list (FEL) | Statistics |
|---|---|---|---|---|---|---|---|
| **t** | **(x, y, z, ...)** | | | | | $(3,t_1)$ – Type 3 event to occur at $t_1$ | |
| **...** | **...** | **...** | **...** | **...** | **...** | **...** | **...** |

# The Event Scheduling / Time Advance Algorithm

# Event-scheduling/Time-advance algorithm

- Future event list (FEL)
  - All event notices are chronologically ordered in the FEL
  - At current time $t$, the FEL contains all scheduled events
  - The event times satisfy: $t < t_1 \leq t_2 \leq t_3 \leq \ldots \leq t_n$
  - The event associated with $t_1$ is the imminent event, i.e., the next event to occur
  - Scheduling of an event
    - At the beginning of an activity the duration is computed and an end-of-activity event is placed on the future event list
  - The content of the FEL is changing during simulation run
    - Efficient management of the FEL has a major impact on the performance of a simulation run
    - Data structures and algorithms
      - Array, List, Tree, Heap etc.

# Event-scheduling/Time-advance algorithm

**Event-scheduling/Time-advance algorithm**

- Step 1: Remove the event notice for the imminent event from FEL
  - event (3, $t_1$) in the example
- Step 2: Advance Clock to imminent event time
  - Set clock = $t_1$
- Step 3: Execute imminent event
  - update system state
  - change entity attributes
  - set membership as needed
- Step 4: Generate future events and place their event notices on FEL
  - Event (4, t*)
- Step 5: Update statistics and counters

Old system snapshot at time t

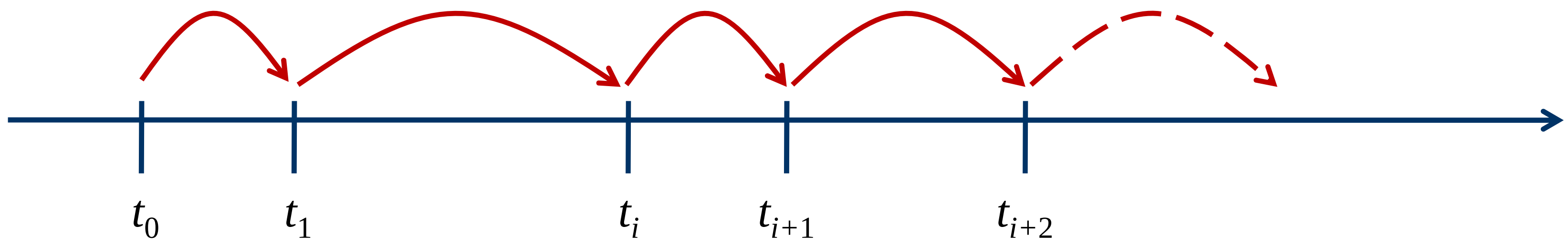
| Clock | State | … | Future event list |
|---|---|---|---|
| t | (5,1,6) | | $(3,t_1)$ – Type 3 event to occur at $t_1$ |
| | | | $(1,t_2)$ – Type 1 event to occur at $t_2$ |
| | | | $(1,t_3)$ – Type 1 event to occur at $t_3$ |
| | | | ... |
| | | | $(2,t_n)$ – Type 2 event to occur at $t_n$ |

New system snapshot at time $t_1$

| Clock | State | … | Future event list |
|---|---|---|---|
| $t_1$ | (5,1,5) | | $(1,t_2)$ – Type 1 event to occur at $t_2$ |
| | | | (4,t*) – Type 4 event to occur at t* |
| | | | $(1,t_3)$ – Type 1 event to occur at $t_3$ |
| | | | ... |
| | | | $(2,t_n)$ – Type 2 event to occur at $t_n$ |

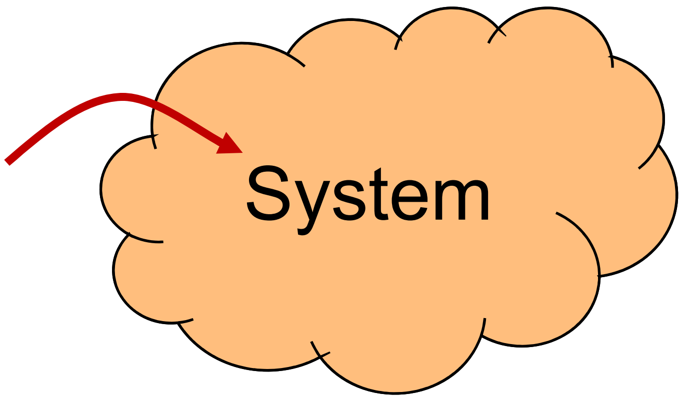
# Event-scheduling/Time-advance algorithm

- Evolution of the system state (snapshots)



# Event-scheduling/Time-advance algorithm

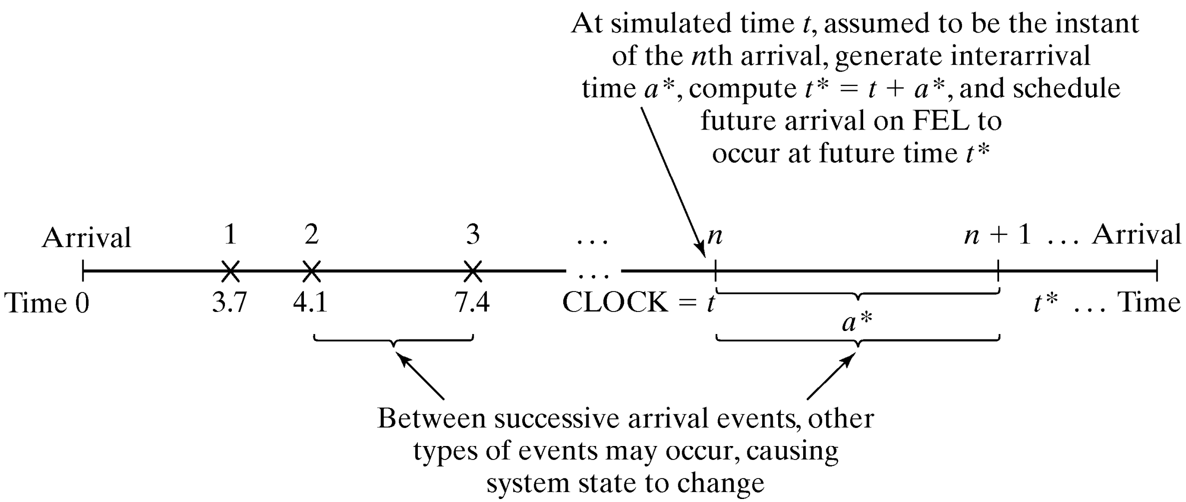
- System snapshot at time 0
  - Initial conditions
  - Generation of exogenous events
    - Exogenous event, is an event which happens outside the system, but impinges on the system, e.g., arrival of a customer.



# Event-scheduling/Time-advance algorithm

- Generation of events
  - Arrival of a customer
    - At $t$=0 first arrival is generated and scheduled
    - When the clock is advanced to the time of the first arrival, a second arrival is generated
    - Generate an interarrival time $a*$
    - Calculate $t* = clock + a*$
    - Place event notice at $t*$ on the FEL

Bootstrapping

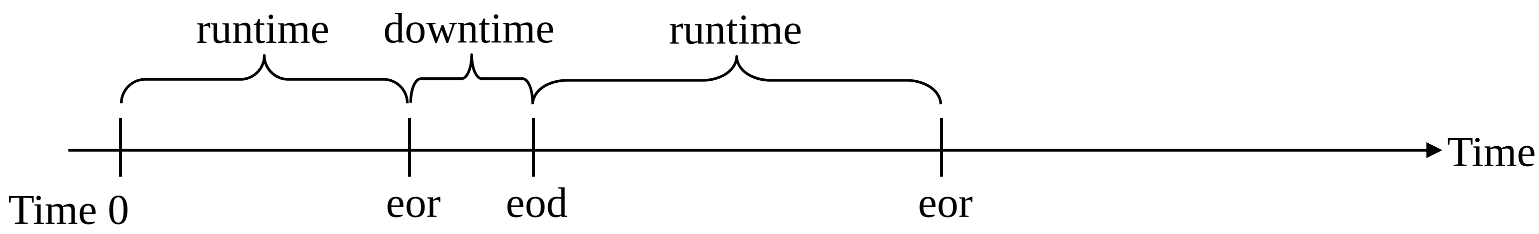


# Event-scheduling/Time-advance algorithm

- Generation of events
  - Service completion of a customer
    - A customer completes service at $t$
    - If the next customer is present a new service time $s*$ is generated
    - Calculate $t* = \text{clock} + s*$
    - Schedule next service completion at $t*$
    - Additionally: Service completion event will be scheduled at the arrival time, when there is an idle server
    - Service time is an activity
    - Beginning service is a conditional event
      - Conditions: Customer is present and server is idle
    - Service completion is a primary event

# Event-scheduling/Time-advance algorithm

- Generation of events
  - Alternate generation of runtimes and downtimes
    - At time 0, the first runtime will be generated and an end-of-runtime event will be scheduled
    - Whenever an end-of-runtime (eor) event occurs, a downtime will be generated, and an end-of-downtime (eod) event will be scheduled
    - At the end-of-downtime event, a runtime is generated and an end-of-runtime event is scheduled
    - Runtimes and downtimes are activities
    - end-of-runtime and end-of-downtime are primary events



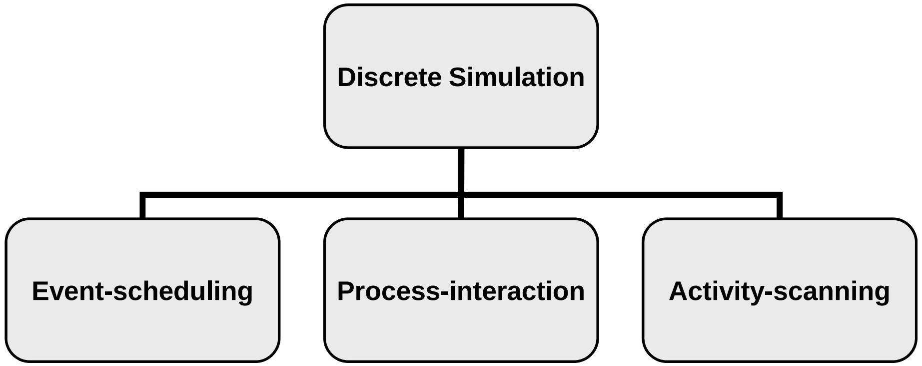
# Event-scheduling/Time-advance algorithm

- Stopping a simulation
  1. At time 0, schedule a stop simulation event at a specified future time $T_E$ ➡ Simulation will run over $[0, T_E]$
  2. Run length $T_E$ is determined by the simulation itself.
     - $T_E$ is not known ahead.
     - Example 1: $T_E$ = When FEL is empty
     - Example 2: $T_E$ = When $k$-th customer leaves the system

# World Views

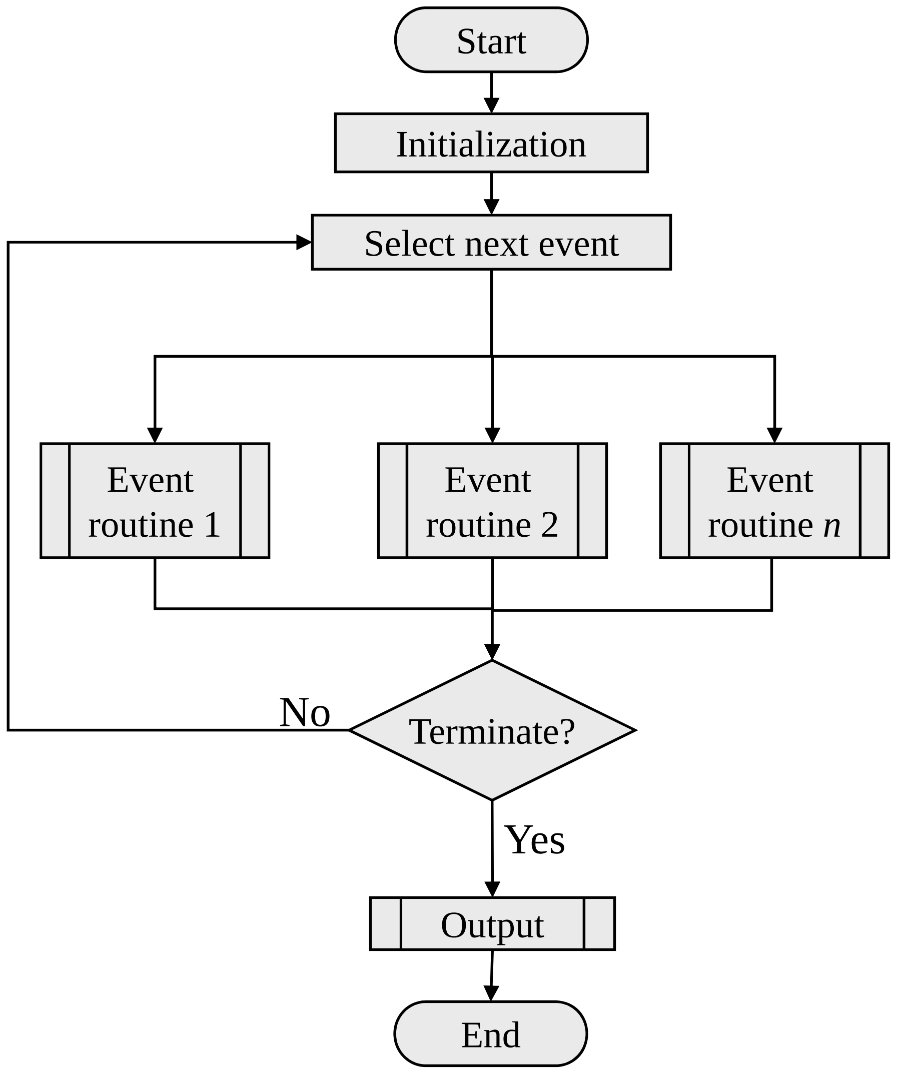
# World Views

- World view
  - A world view is an orientation for the model developer
  - Simulation packages typically support some world views
  - Here, only world views for discrete simulations



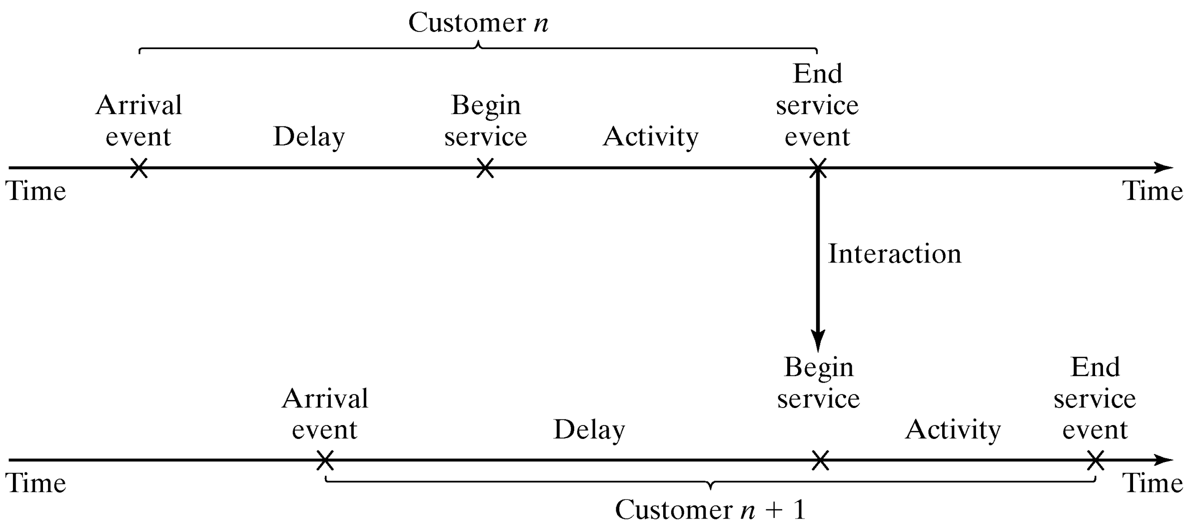
# World Views

- Event-scheduling
  - Focus on events
  - Identify the entities and their attributes
  - Identify the attributes of the system
  - Define what causes a change in system state
  - Write a routine to execute for each event
  - Variable time advance



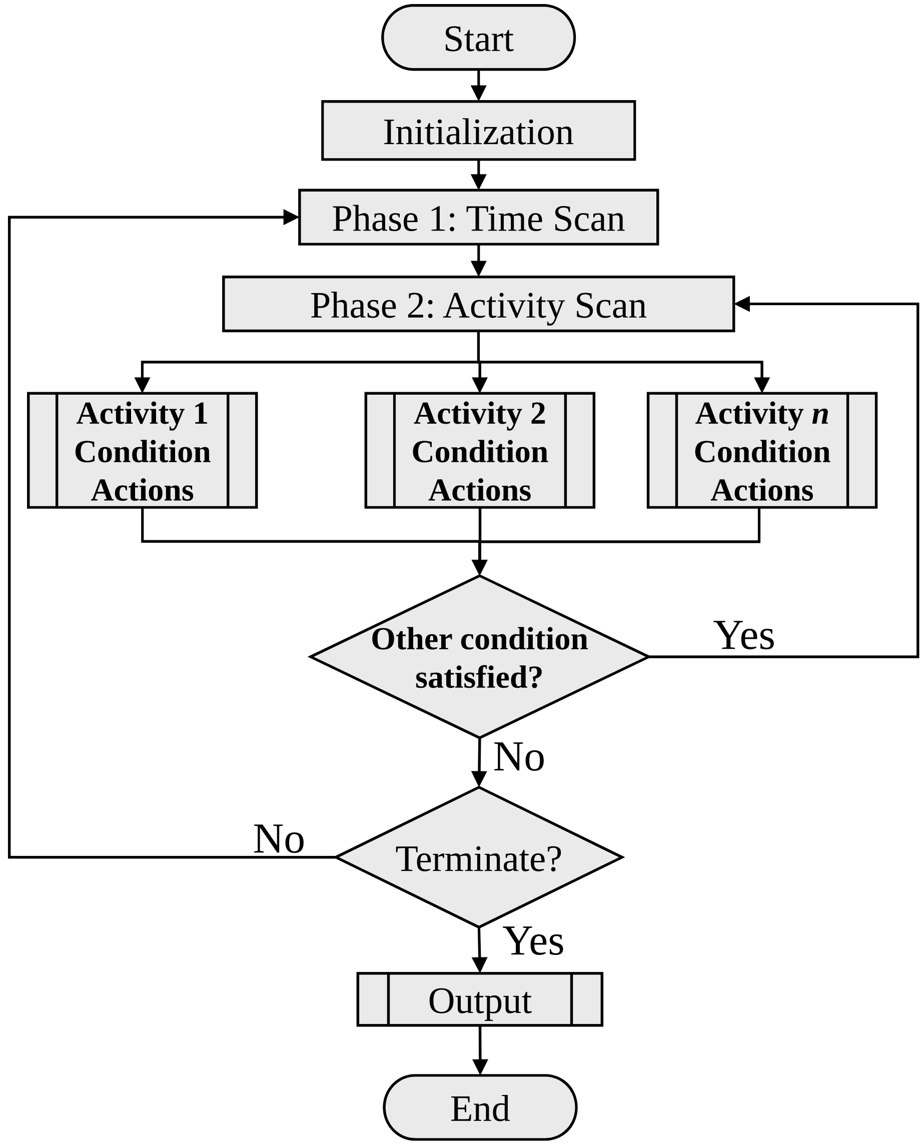
# World Views

- Process-interaction
  - Modeler thinks in terms of processes
  - A process is the lifecycle of one entity, which consists of various events and activities
  - Simulation model is defined in terms of entities or objects and their life cycle as they flow through the system, demanding resources and queueing to wait for resources
  - Some activities might require the use of one or more resources whose capacities are limited
  - Processes interact, e.g., one process has to wait in a queue because the resource it needs is busy with another process
  - A process is a time-sequenced list of events, activities and delays, including demands for resources, that define the life cycle of one entity as it moves through a system
  - Variable time advance



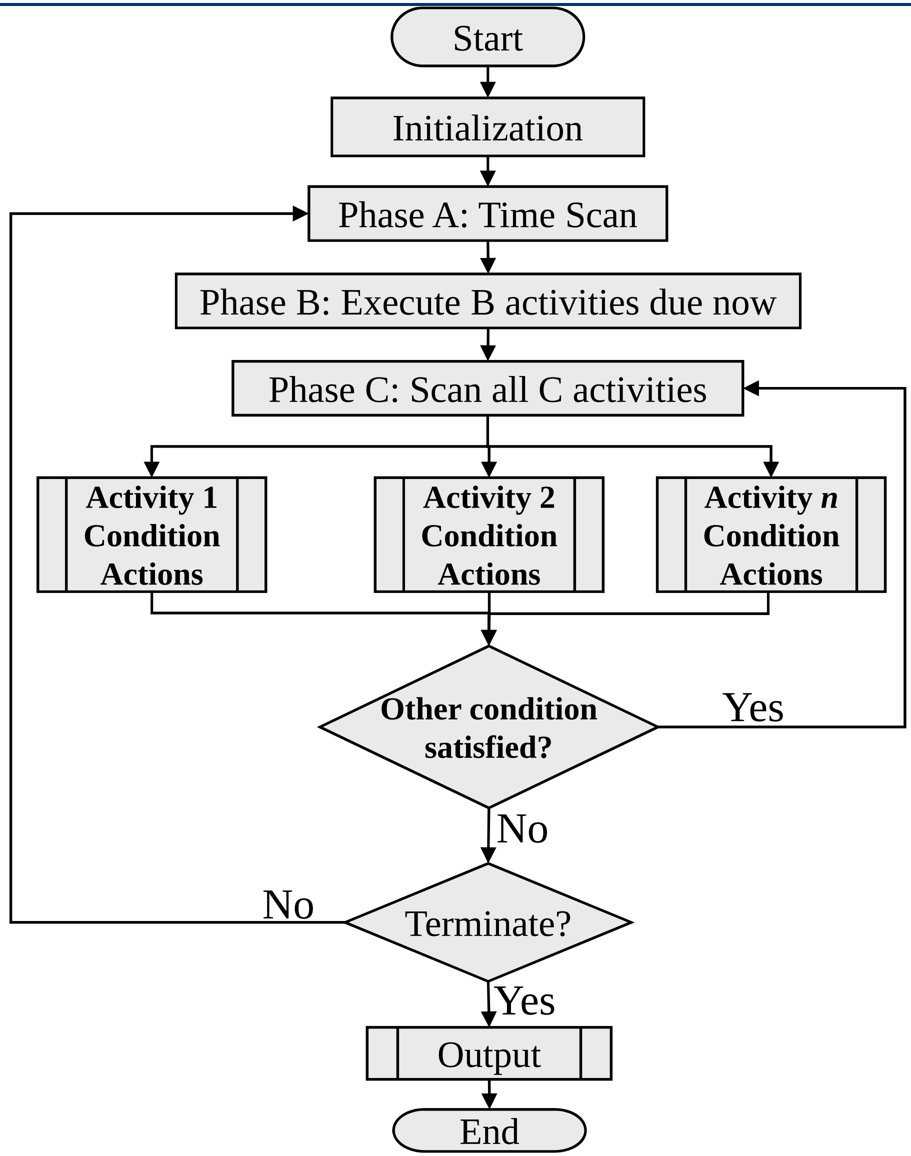
# World Views

- Activity-scanning
  - Modeler concentrates on activities of a model and those conditions that allow an activity to begin
  - At each clock advance, the conditions for each activity are checked, and, if the conditions are true, then the corresponding activity begins
  - Fix time advance
  - Disadvantage: The repeated scanning to discover whether an activity can begin results in slow runtime
  - Improvement: Three-phase approach
    - Combination of event scheduling with activity scanning

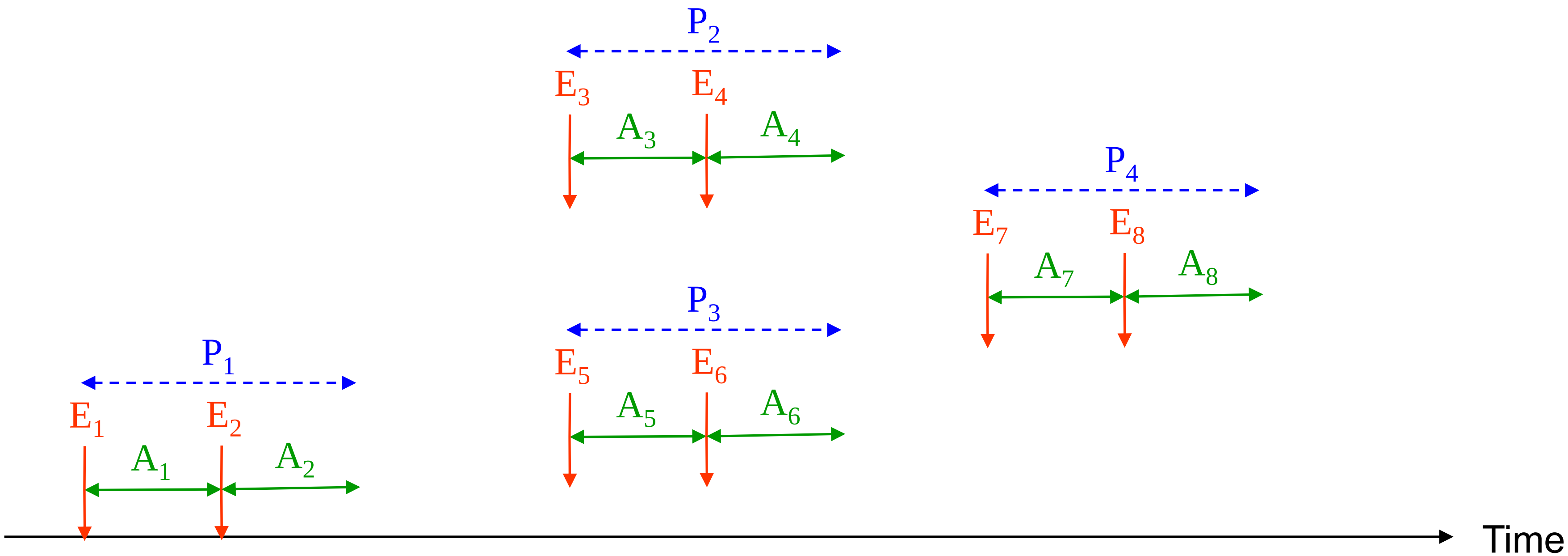


# World Views

- Three-phase approach
  - Events are activities of duration zero time units
  - Two types of activities
    - **B activities:** activities bound to occur; all primary events and unconditional activities
    - **C activities:** activities or events that are conditional upon certain conditions being true
  - The B-type activites can be scheduled ahead of time, just as in the event-scheduling approach
    - Variable time advance
    - FEL contains only B-type events
  - Scanning to learn whether any C-type activities can begin or C-type events occur happen only at the end of each time advance, after all B-type events have completed



# World Views

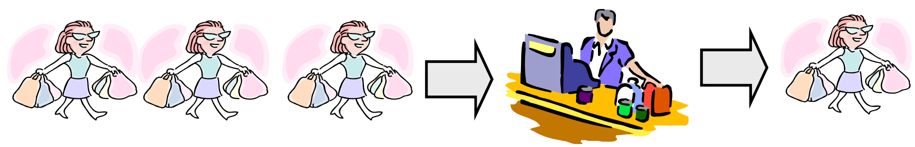


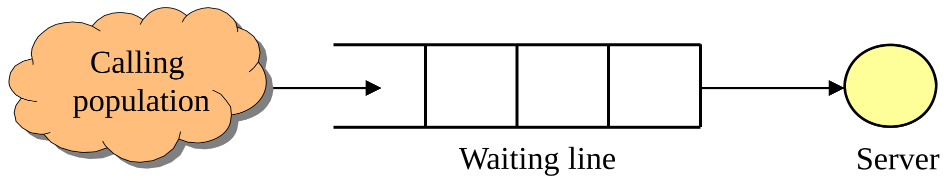
# Examples

Example 1

# Manual Simulation Using Event Scheduling: Grocery

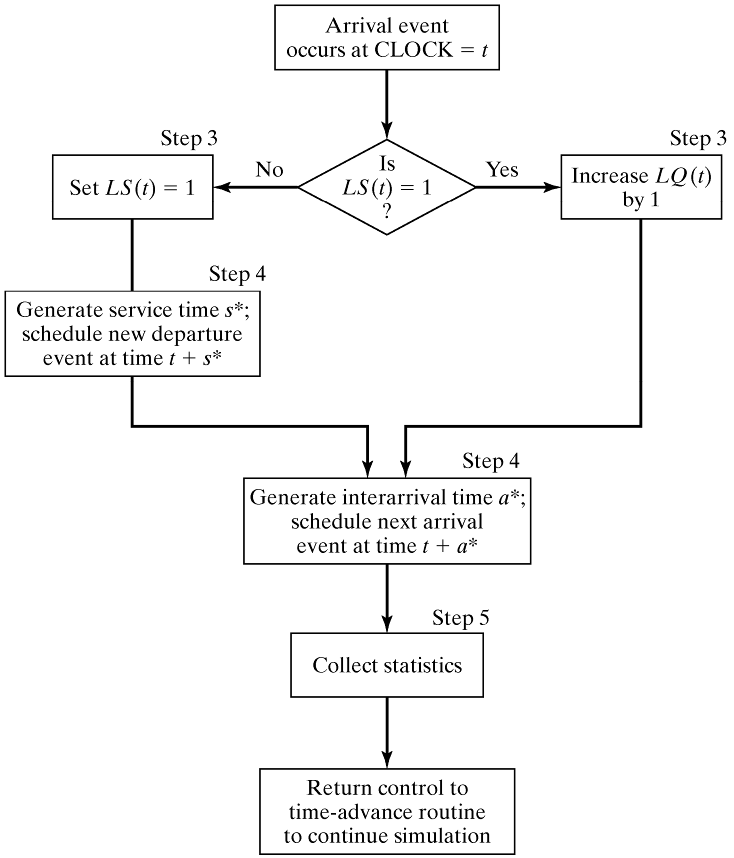
- Reconsider the grocery example from Chapter 2
  - In Chapter 2: We used an ad hoc method to simulate the grocery
- System state at time $t$ is given by $[\ \mathrm{LQ}(t), \mathrm{LS}(t)\ ]$
  - $\mathrm{LQ}(t)$ = Number of customers in the waiting line at $t$
  - $\mathrm{LS}(t)$ = Number of customers being served at $t$ (0 or 1)
- Entities
  - Server and customers are not explicitly modeled
- Events
  - Arrival (A)
  - Departure (D)
  - Stopping event (E)
- Event notices
  - (A, t) arrival event at future time t
  - (D, t) departure event at future time t
  - (E, t) simulation stop at future time t
- Activities
  - Interarrival time
  - Service time
- Delay
  - Time customer spent in waiting line

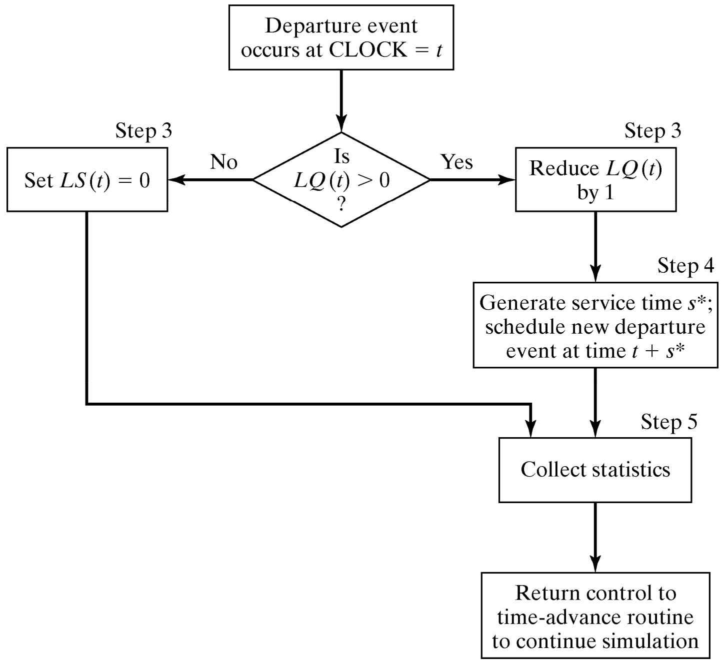




# Manual Simulation Using Event Scheduling: Grocery

- System state = [ LQ(t), LS(t) ] is affected by the events
  - Arrival
  - Departure



# Manual Simulation Using Event Scheduling: Grocery

| | System State | | | | Cumulative Statistics | |
|---|---|---|---|---|---|---|
| *Clock* | *LQ(t)* | *LS(t)* | *Future Event List* | *Comment* | *B* | *MQ* |
| 0 | 0 | 1 | (A, 1) (D, 4) (E, 60) | First A occurs<br>($a^* = 1$) Schedule next A<br>($s^* = 4$) Schedule first D | 0 | 0 |
| 1 | 1 | 1 | (A, 2) (D, 4) (E, 60) | Second A occurs: (A, 1)<br>($a^* = 1$) Schedule next A<br>(Customer delayed) | 1 | 1 |
| 2 | 2 | 1 | (D, 4) (A, 8) (E, 60) | Third A occurs: (A, 2)<br>($a^* = 6$) Schedule next A<br>(Two customers delayed) | 2 | 2 |
| 4 | 1 | 1 | (D, 6) (A, 8) (E, 60) | First D occurs: (D, 4)<br>($s^* = 2$) Schedule next D<br>(Customer delayed) | 4 | 2 |
| 6 | 0 | 1 | (A, 8) (D, 11) (E, 60) | Second D occurs: (D, 6)<br>($s^* = 5$) Schedule next D | 6 | 2 |
| 8 | 1 | 1 | (D, 11) (A, 11) (E, 60) | Fourth A occurs: (A, 8)<br>($a^* = 3$ Schedule next A<br>(Customer delayed) | 8 | 2 |
| 11 | 1 | 1 | (D, 15) (A, 18) (E, 60) | Fifth A occurs: (A, 11)<br>($a^* = 7$) Schedule next A<br>Third D occurs: (D, 11)<br>($s^* = 4$) Schedule next D<br>Customer delayed | 11 | 2 |
| 15 | 0 | 1 | (D, 16) (A, 18) (E, 60) | Fourth D occurs: (D, 15)<br>($s^* = 1$) Schedule next D | 15 | 2 |
| 16 | 0 | 0 | (A, 18) (E, 60) | Fifth D occurs: (D, 16) | 16 | 2 |
| 18 | 0 | 1 | (D, 23) (A, 23) (E, 60) | Sixth A occurs<br>($a^* = 5$) Schedule next A<br>($s^* = 5$) Schedule next D | 16 | 2 |
| $\boxed{23}$ | 0 | 1 | (A, 25) (D, 27) (E, 60) | Seventh A occurs: (A, 23)<br>($a^* = 2$) Schedule next Arrival<br>Sixth D occurs: (D, 23) | $\boxed{21}$ | $\boxed{2}$ |

Server Busy time

Maximum Queue Length

**Initial conditions**

- First customer arrives at t=0 and gets service
- An arrival and a departure event is on FEL

- Server was busy for 21 of 23 time units
- Maximum queue length was 2

## Manual Simulation Using Event Scheduling: Grocery

- When event scheduling is implemented, consider
  - Only one snapshot is kept in the computer memory
  - A new snapshot can be derived **only** from the previous snapshot
  - Past snapshots are ignored for advancing the clock
  - The current snapshot must contain **all information necessary** to continue the simulation!

- In the example
  - No information about particular customer
  - If needed, the model has to be extended

## Manual Simulation Using Event Scheduling: Grocery

- Analyst wants estimates per customer basis
  - Mean response time (system time)
  - Mean proportion of customers who spend more than 5 time units

- Extend the model to represent customers explicitly
  - Entities: Customer entities denoted as C1, C2, C3, …
    - (Ci, t) customer Ci arrived at t
  - Event notices
    - (A, t, Ci) arrival of customer Ci at t
    - (D, t, Cj) departure of customer Cj at t
  - Set
    - "Checkout Line" set of customers currently at the checkout counter ordered by time of arrival
  - Statistics (updated when a departure event occurs)
    - S: sum of customer response times for all customers who have departed by the current time
    - F: total number of customers who spend ≥ 5 time units
    - $N_D$: number of departures up to the current simulation time

# Manual Simulation Using Event Scheduling: Grocery

S = Sum response time
$N_D$ = # Customers left
F = # Customer which spent ≥ 5 TU

Extended version of the simulation table from Slide 3.32

| | System State | | Lists | | Statistics | | |
|---|---|---|---|---|---|---|---|
| Clock | LQ(t) | LS(t) | Checkout Line | Future Event List | S | $N_D$ | F |
| 0 | 0 | 1 | (C1,0) | (A,1,C2) (D,4,C1)(E,60) | 0 | 0 | 0 |
| 1 | 1 | 1 | (C1,0)(C2,1) | (A,2,C3)(D,4,C1)(E,60) | 0 | 0 | 0 |
| 2 | 2 | 1 | (C1,0)(C2,1)(C3,2) | (D,4,C1)(A,8,C4)(E,60) | 0 | 0 | 0 |
| 4 | 1 | 1 | (C2,1)(C3,2) | (D,6,C2)(A,8,C4)(E,60) | 4 | 1 | 0 |
| 6 | 0 | 1 | (C3,2) | (A,8,C4)(D,11,C3)(E,60) | 9 | 2 | 1 |
| 8 | 1 | 1 | (C3,2)(C4,8) | (D,11,C3)(A,11,C5)(E,60) | 9 | 2 | 1 |
| 11 | 1 | 1 | (C4,8)(C5,11) | (D,15,C4)(A,18,C6)(E,60) | 18 | 3 | 2 |
| 15 | 0 | 1 | (C5,11) | (D,16,C4)(A,18,C6)(E,60) | 25 | 4 | 3 |
| 16 | 0 | 0 | | (A,18,C6)(E,60) | 30 | 5 | 4 |
| 18 | 0 | 1 | (C6,18) | (D,23,C6)(A,23,C7)(E,60) | 30 | 5 | 4 |
| 23 | 0 | 1 | (C7,23) | (A,25,C8)(D,27,C7)(E,60) | 35 | 6 | 5 |

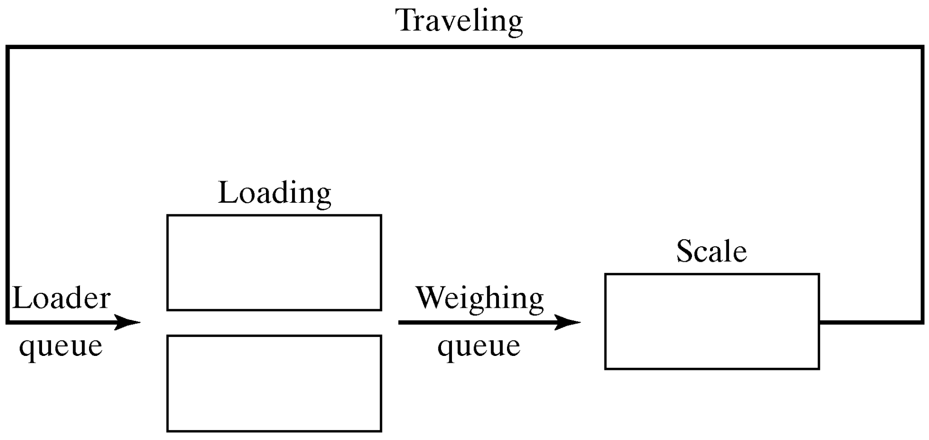
$$\overline{\text{response time}} = \frac{S}{N_D} = \frac{35}{6} = 5.83 \qquad N_{\geq 5} = \frac{F}{N_D} = \frac{5}{6} = 0.83$$

# Examples

## Example 2

# Manual Simulation Using Event Scheduling: Dump Truck

- The DumpTruck Problem
  - Six dump trucks are used to haul coal from the entrance of a small mine to the railroad
  - Each truck is loaded by one of two loaders
  - After loading, the truck immediately moves to the scale, to be weighed
  - Loader and Scale have a first-come-first-serve (FCFS) queue
  - The travel time from loader to scale is negligible
  - After being weighed, a truck begins to travel, afterwards unloads the coal and returns to the loader queue
  - Purpose of the study: Estimation of the loader and scale utilizations.



# Manual Simulation Using Event Scheduling: Dump Truck

- System state [ LQ(t), L(t), WQ(t), W(t) ]
  - LQ(t) = number of trucks in the loader queue $\in\{0,1,2,...\}$
  - L(t) = number of trucks being loaded $\in\{0,1,2\}$
  - WQ(t) = number of trucks in weigh queue $\in\{0,1,2,...\}$
  - W(t) = number of trucks being weighed $\in\{0,1\}$
- Event notices
  - (ALQ, t, DTi) dump truck i arrives at loader queue (ALQ) at time t
  - (EL, t, DTi) dump truck i ends loading (EL) at time t
  - (EW, t, DTi) dump truck i ends weighing (EW) at time t
- Entities
  - The six dump trucks DT1, DT2, ..., DT6
- Lists
  - Loader queue: Trucks waiting to begin loading, FCFS
  - Weigh queue: Trucks waiting to be weighed, FCFS
- Activities
  - Loading: Loading time
  - Weighing: Weighing time
  - Travel: Travel time
- Delays
  - Delay at loader queue
  - Delay at scale

**Loading Time Distribution**

| Loading Time | PDF | CDF |
|---|---|---|
| 5 | 0.30 | 0.30 |
| 10 | 0.50 | 0.80 |
| 15 | 0.20 | 1.00 |

**Weighing Time Distribution**

| Weighing Time | PDF | CDF |
|---|---|---|
| 12 | 0.70 | 0.70 |
| 16 | 0.30 | 1.00 |

**Travel Time Distribution**

| Travel Time | PDF | CDF |
|---|---|---|
| 40 | 0.40 | 0.40 |
| 60 | 0.30 | 0.70 |
| 80 | 0.20 | 0.90 |
| 100 | 0.10 | 1.00 |

# Manual Simulation Using Event Scheduling: Dump Truck

- Initialization
  - It is assumed that five trucks are at the loader and one is at the scale at time 0
- Activity times
  - Loading time: 10, 5, 5, 10, 15, 10, 10
  - Weighing time: 12, 12, 12, 16, 12, 16
  - Travel time: 60, 100, 40, 40 80
- Statistics
  - BL: Total busy time of both loaders
  - BS: Total busy time of the scale

Both loaders are busy!

| | System State | | | | Lists | | | Statistics | |
|---|---|---|---|---|---|---|---|---|---|
| **Clock** | **LQ(t)** | **L(t)** | **WQ(t)** | **W(t)** | **Loader Queue** | **Weigh Queue** | **Future Event List** | **BL** | **BS** |
| 0 | 3 | 2 | 0 | 1 | DT4, DT5, DT6 | | (EL,5,DT3) (EL,10,DT2) (EW,12,DT1) | 0 | 0 |
| 5 | 2 | 2 | 1 | 1 | DT5, DT6 | DT3 | (EL,10,DT2) (EL,5+5,DT4) (EW,12,DT1) | 10 | 5 |
| 10 | 1 | 2 | 2 | 1 | DT6 | DT3, DT2 | (EL,10,DT4) (EW,12,DT1) (EL,10+10,DT5) | 20 | 10 |
| 10 | 0 | 2 | 3 | 1 | | DT3, DT2, DT4 | (EW,12,DT1) (EL,20,DT5) (EL,10+15,DT6) | 20 | 10 |
| 12 | 0 | 2 | 2 | 1 | | DT2, DT4 | (EL,20,DT5) (EW,12+12,DT3) (EL,25,DT6) (ALQ,12+60,DT1) | 24 | 12 |
| 20 | 0 | 1 | 3 | 1 | | DT2, DT4, DT5 | (EW,24,DT3) (EL,25,DT6) (ALQ,72,DT1) | 40 | 20 |
| 24 | 0 | 1 | 2 | 1 | | DT4, DT5 | (EL,25,DT6) (EW,24+12,DT2) (ALQ,72,DT1) (ALQ,24+100,DT3) | 44 | 24 |

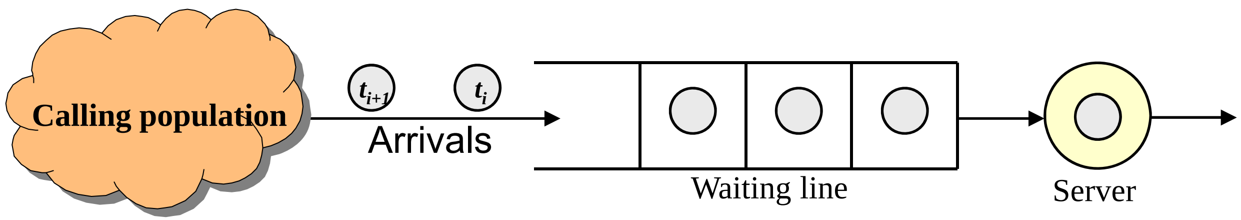
# Implementation of Simulations

Simulation in Java

# Simulation in Java

- Java is a general purpose programming language
  - Object-oriented
- First simple specific simulation implementation
- Later, object-oriented framework for discrete event simulation

- Again the grocery example
  - Single server queue
  - Run for 1000 customers
  - Interarrival times are exponentially distributed with mean 4.5
  - Service times are also exponentially distributed with mean 3.2
  - Known as: M/M/1 queueing system

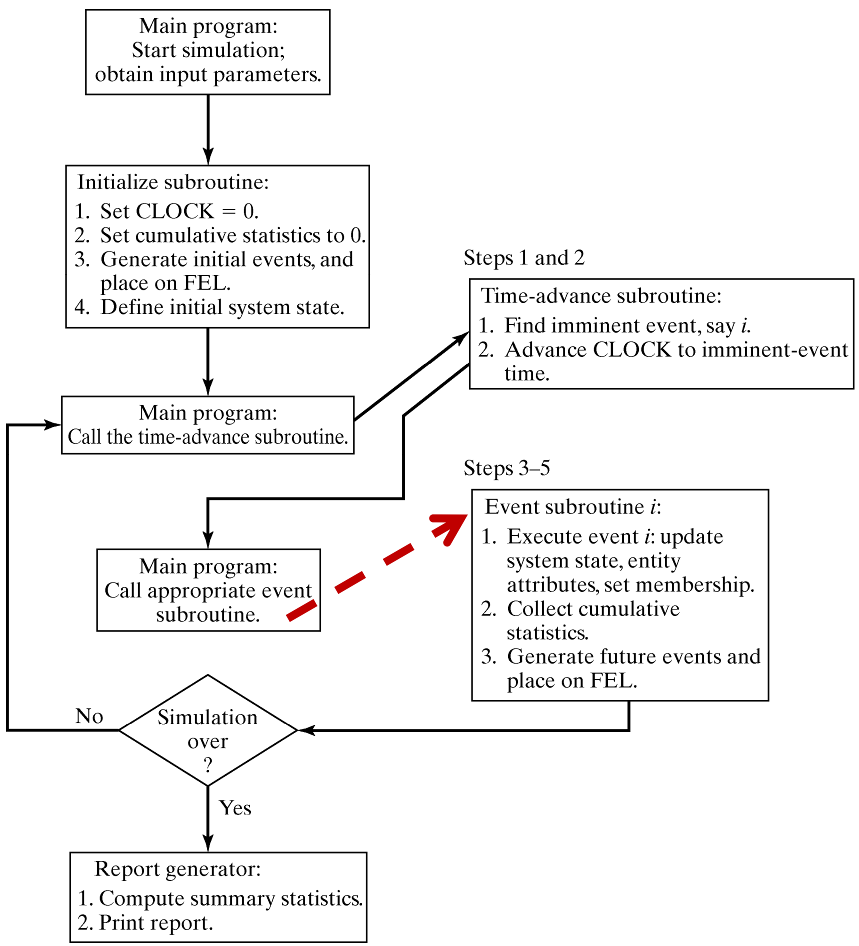


# Simulation in Java

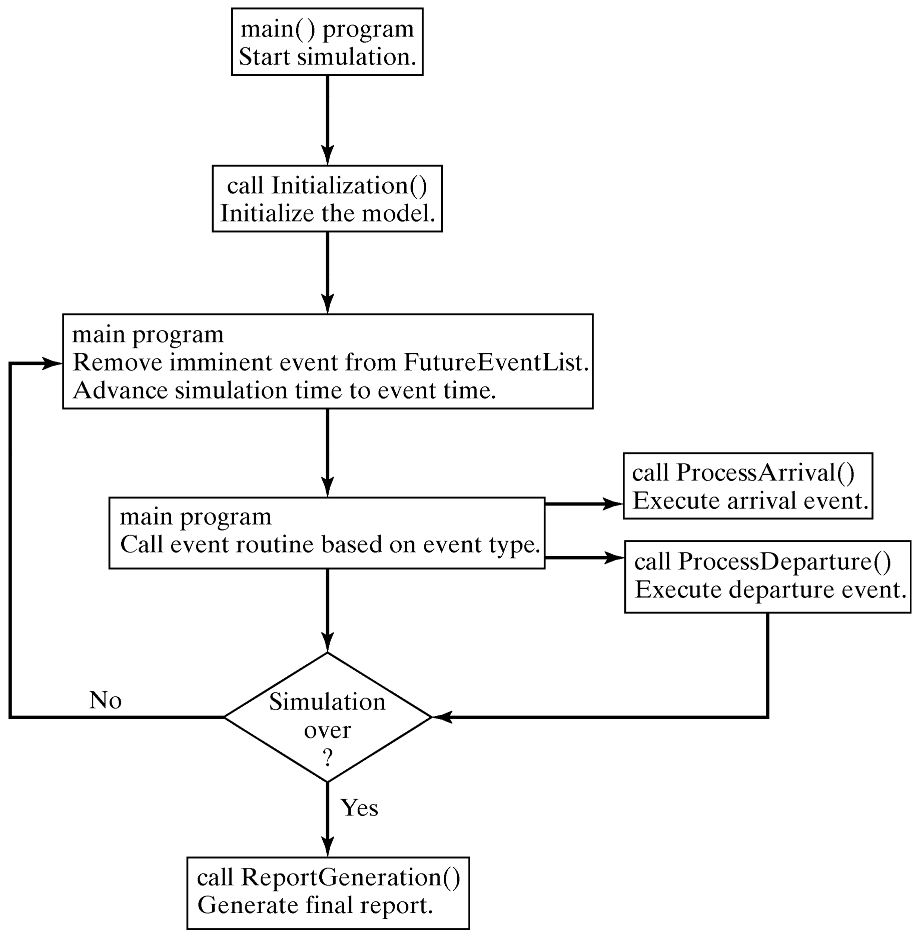
- System state
  - queueLength
  - numberInService
- Entity attributes
  - customers
- Future event list
  - futureEventList
- Activity durations
  - meanInterArrivalTime
  - meanServiceTime
- Input parameters
  - meanInterarrivalTime
  - meanServiceTime
  - totalCustomers
- Simulation variables
  - clock
  - lastEventTime
  - totalBusy
  - maxQueueLength
  - sumResponseTime
- Statistics
  - rho = BusyTime/Clock
  - avgr = Average response time
  - pc4 = Number of customers who spent more than 4 minutes
- Help functions
  - exponential(mu)
- Methods
  - initialization
  - processArrival
  - processDeparture
  - reportGeneration

# Simulation in Java

Overall structure of an event-scheduling simulation program




Overall structure of the Java program



# Simulation in Java: Class Event

A very simple realization of an event

- Only two attributes: type and time

```java
class Event {
    public double time;
    private int type;

    public Event(int _type, double _time) {
          type = _type;
          time = _time;
    }

    public int getType() {
          return type;
    }

    public double getTime() {
          return time;
    }
}
```

# Simulation in Java: Sim Class

```
class Sim {
    // Class Sim variables
    public static double clock,
                         meanInterArrivalTime,
                         meanServiceTime,
                         lastEventTime,
                         totalBusy,
                         maxQueueLength,
                         sumResponseTime;

    public static long  numberOfCustomers,
                        queueLength,
                        numberInService,
                        totalCustomers,
                        numberOfDepartures,
                        longService;

    public final static int arrival = 1;            // Event type for an arrival
    public final static int departure = 2;          // Event type for a departure

    public static EventList futureEventList;        // We use these data structures as
    public static Queue customers;                  // given by the system.
    public static Random stream;                    // A random number generator
```

# Simulation in Java: Main program

```
public static void main(String argv[]) {
          meanInterArrivalTime = 4.5;
          meanServiceTime      = 3.2;
          totalCustomers       = 1000;
          long seed            = Long.parseLong(argv[0]);

          stream = new Random(seed);              // Initialize RNG stream
          futureEventList = new EventList();      // Initialize the FEL
          customers = new Queue();               // Set which holds the customers

          initialization();                       // Initialize the simulation

          // Loop until first "totalCustomers" have departed
          while( numberOfDepartures < totalCustomers ) {
              Event event = (Event)futureEventList.getMin();    // Get imminent event
              futureEventList.dequeue();                        // Be rid of it
              clock = event.getTime();                          // Advance simulation time
              if( event.getType() == arrival ) {
                  processArrival(event);                        // Call event function
              }
              else {
                  processDeparture(event);                      // Call event function
              }
          }

          reportGeneration();                                   // Print statistics
     }
```

# Simulation in Java: Initialization

```java
// Seed the event list with TotalCustomers arrivals
public static void initialization()   {
    clock = 0.0;
    queueLength = 0;
    numberInService = 0;
    lastEventTime = 0.0;
    totalBusy = 0 ;
    maxQueueLength = 0;
    sumResponseTime = 0;
    numberOfDepartures = 0;
    longService = 0;

    // Create first arrival event
    double eventTime = exponential(stream, meanInterArrivalTime);
    Event event = new Event(arrival, eventTime);
    futureEventList.enqueue(event);
}
```

# Simulation in Java: Event Arrival

```java
public static void processArrival(Event event) {
    customers.enqueue(event);
    queueLength++;
    // If the server is idle, fetch the event, do statistics and put into service
    if( numberInService == 0 ) {
          scheduleDeparture();
    }
    else {
          totalBusy += (clock - lastEventTime);  // server is busy
    }

    // Adjust max queue length statistics
    if(maxQueueLength < queueLength) {
          maxQueueLength = queueLength;
    }

    // Schedule the next arrival
    Double eventTime = clock + exponential(stream, meanInterArrivalTime);
    Event nextArrival = new Event(arrival, eventTime);
    futureEventList.enqueue( nextArrival );
    lastEventTime = clock;
}
```

# Simulation in Java: Event Departure

```java
public static void scheduleDeparture() {
    double serviceTime = exponential(stream, meanServiceTime);
    Event depart = new Event(departure, clock + serviceTime);
    futureEventList.enqueue(depart);
    numberInService = 1;
    queueLength--;
}

public static void processDeparture(Event e) {
    // Get the customer description
    Event finished = (Event) customers.dequeue();
    // If there are customers in the queue then schedule the departure of the next one
    if( queueLength > 0 ) {
          scheduleDeparture();
    }
    else {
          numberInService = 0;
    }
    // Measure the response time and update cumulative statistics
    double response = clock - finished.getTime();
    sumResponseTime += response;
    if( response > 4.0 )
          longService++; // record long service
    totalBusy += (clock - lastEventTime);
    numberOfDepartures++;
    lastEventTime = clock;
}
```

# Simulation in Java: Report Generator

```java
public static void reportGeneration() {
    double rho   = totalBusy/clock;
    double avgr  = sumResponseTime/totalCustomers;
    double pc4   = ((double)longService)/totalCustomers;

    System.out.println( "SINGLE SERVER QUEUE SIMULATION - GROCERY STORE CHECKOUT COUNTER ");
    System.out.println( "\tMEAN INTERARRIVAL TIME                    " + meanInterArrivalTime );
    System.out.println( "\tMEAN SERVICE TIME                         " + meanServiceTime );
    System.out.println( "\tNUMBER OF CUSTOMERS SERVED                " + totalCustomers );
    System.out.println();
    System.out.println( "\tSERVER UTILIZATION                        " + rho );
    System.out.println( "\tMAXIMUM LINE LENGTH                       " + maxQueueLength );
    System.out.println( "\tAVERAGE RESPONSE TIME                     " + avgr + "  Time Units");
    System.out.println( "\tPROPORTION WHO SPEND FOUR ");
    System.out.println( "\t MINUTES OR MORE IN SYSTEM                " + pc4 );
    System.out.println( "\tSIMULATION RUNLENGTH                      " + clock + " Time Units");
    System.out.println( "\tNUMBER OF DEPARTURES                      " + totalCustomers );
}
```

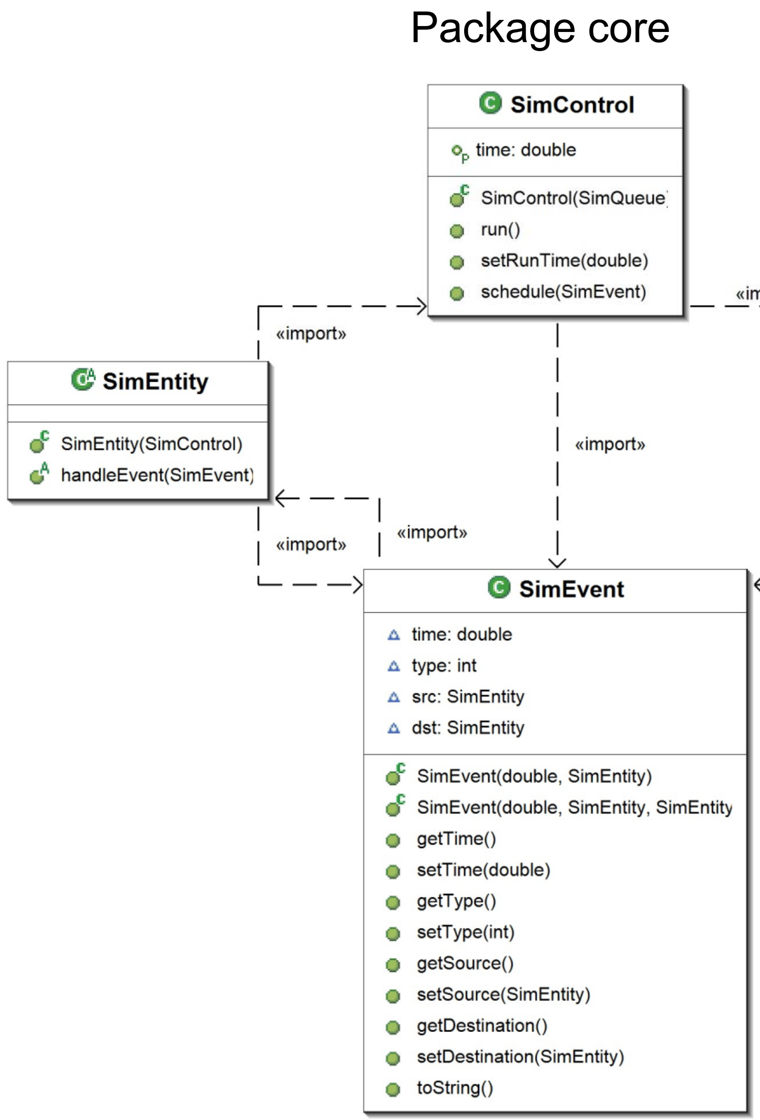
# Simulation in Java: Output

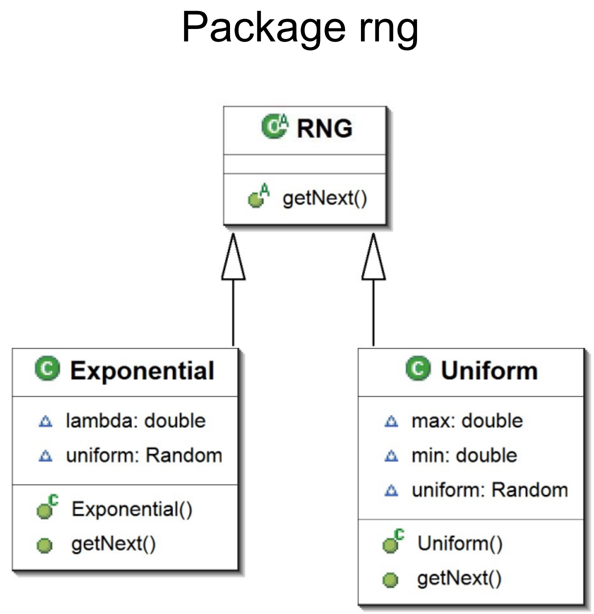
```
SINGLE SERVER QUEUE SIMULATION - GROCERY STORE CHECKOUT COUNTER
        MEAN INTERARRIVAL TIME                              4.5
        MEAN SERVICE TIME                                   3.2
        NUMBER OF CUSTOMERS SERVED                          1000

        SERVER UTILIZATION                                  0.718
        MAXIMUM LINE LENGTH                                 13.0
        AVERAGE RESPONSE TIME                               9.563
        PROPORTION WHO SPEND FOUR
         MINUTES OR MORE IN SYSTEM                          0.713
        SIMULATION RUNLENGTH                                4485.635
        NUMBER OF DEPARTURES                                1000
```

# Implementation of Simulations

OO-Discrete-Event Simulation Framework

# Object-Oriented Simulation Framework



# Object-Oriented Simulation Framework

- OO Discrete-Event Simulation Framework consists of
  - Two packages

- Package core
  - SimEvent
  - SimEntity
  - SimQueue
  - SimControl

- Package rng
  - RNG

# Object-Oriented Simulation Framework

```
public class SimEvent {
    double time;
    int type;
    SimEntity src;
    SimEntity dst;
    public long id;

    public SimEvent(SimEntity _dst) {
        type = 0;
        time = 0;
        src = null;
        dst = _dst;
    }

    public SimEvent(double _time, SimEntity _dst) {
        type = 0;
        time = _time;
        src = null;
        dst = _dst;
    }

    public SimEvent(double _time, SimEntity _src, SimEntity _dst) {
        type = 0;
        time = _time;
        src = _src;
        dst = _dst;
    }
```

# Object-Oriented Simulation Framework

```java
public abstract class SimEntity {
    protected SimControl simControl;

    /**
     * An entity has to know the current instance of the simulator.
     * @param _simControl
     * @see SimControl
     */
    public SimEntity(SimControl _simControl) {
          simControl = _simControl;
    }

    /**
     * This method handles the events destined to this entity.
     * @param event
     * @see SimEvent
     */
    abstract public void handleEvent(SimEvent event);
}
```

# Object-Oriented Simulation Framework

```
public abstract class SimQueue {

    /**
     * Schedule the given event according to the event time.
     * @param event
     * @see SimEvent
     */
    abstract public void schedule(SimEvent event);

    /**
     * Return the next event in the queue.
     * @return imminent event in queue.
     * @see SimEvent
     */
    abstract public SimEvent getNextEvent();

    /**
     * This method dumps the content of the queue.
     * It is for debugging purposes.
     */
    abstract public void dump();

    abstract public boolean isEmpty();
}
```

# Object-Oriented Simulation Framework

```
public class SimControl {
    private SimQueue queue;
    private double time;
    private double endTime;

    public SimControl(SimQueue _queue) {
          queue = _queue;
    }
    public void run() {
          SimEvent event;
          while( queue.isEmpty() == false ) {
            // If there is an event in FEL and the sim-end is not reached ...
            event = queue.getNextEvent();
            time = event.getTime();
            if( event.getTime() <= endTime )
                dispatch(event); // ... call the destination object of this event
            else
              break;
          }
    }

    private void dispatch(SimEvent event) {
          event.getDestination().handleEvent(event);
    }
```

# Object-Oriented Simulation Framework

```
... public class SimControl ...

    public void setRunTime(double _runTime) {
          endTime = _runTime;
    }

    public void schedule(SimEvent event) {
          queue.schedule(event);
    }

    public void schedule(SimEvent event, double _delta) {
        event.setTime(time +_delta);
        schedule(event);
    }
```

# Object-Oriented Simulation Framework

```java
public abstract class RNG {
    abstract public double getNext();
}



public class Exponential extends RNG {
    double lambda;
    Random uniform;

    public Exponential(double _lambda) {
        lambda = _lambda;
        uniform = new Random(System.currentTimeMillis());
    }

    /*
     * @see rng.RNG#getNext()
     */
    public double getNext() {
       return -Math.log(uniform.nextDouble())/lambda;
    }

}
```

# Object-Oriented Simulation Framework

- Again our Grocery example
  - Use of the object-oriented simulation framework
- MM1Generator
  - Generates new customer
- MM1Server
  - Serves customer

```java
class MM1Generator extends SimEntity {
    MM1Server dst;
    RNG interarrivalTime;

    int noOfCustomer;
    public double sumInterArrivalTime = 0.0;

    /**
     * Constructor
     */
    public MM1Generator(SimControl _simControl, MM1Server _dst, RNG _random) {
        super(_simControl);
        noOfCustomer = 0;
        dst = _dst;
        interarrivalTime = _random;

        // Schedule the first arrival
        scheduleNextArrival();
    }

    public void handleEvent(SimEvent event) {
        dst.newCustomer(event);
        noOfCustomer++;
        scheduleNextArrival();
    }

    private void scheduleNextArrival() {
        double aInterArrivalTime = interarrivalTime.getNext();
        sumInterArrivalTime += aInterArrivalTime;

        SimEvent event = new SimEvent(this);
        event.id = noOfCustomer;
        simControl.schedule(event, aInterArrivalTime);
    }

    public int getNoOfCustomer() {
        return noOfCustomer;
    }

    public double getLambda () {
        return 1.0/getMeanArrivalTime();
    }

    public double getMeanArrivalTime() {
        return sumInterArrivalTime/(double)noOfCustomer;
    }
}
```

# Object-Oriented Simulation Framework

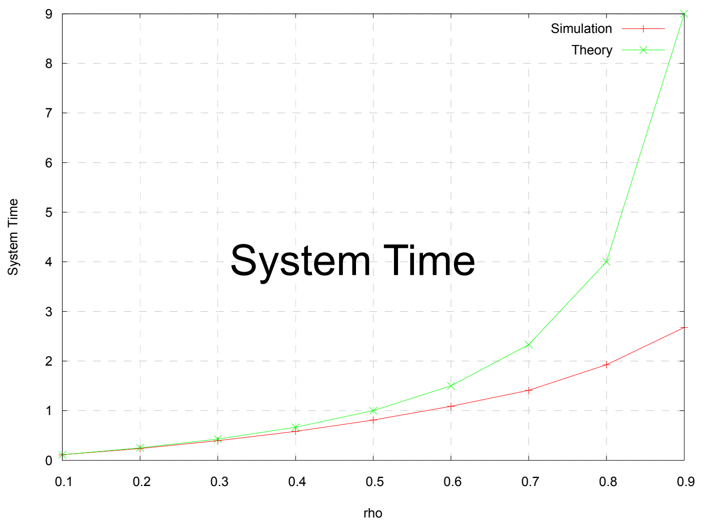
```
class MM1Server extends SimEntity {
    boolean customerInService = false;
    int servicedCustomer = 0;
    double lastServiceStart = 0.0;

    double sumServiceTime = 0.0;
    double sumSystemTime = 0.0;
    double sumQueueTimes = 0.0;

    RNG serviceTime;
    LinkedList customerQueue;

    /**
     * @param _simControl
     */
    public MM1Server(SimControl _simControl, RNG _random) {
        super(_simControl);
        serviceTime = _random;
        customerQueue = new LinkedList();
    }

    public void newCustomer(SimEvent event) {
        customerQueue.add(event);
        if( customerInService == false ) {
            scheduleNextDeparture();
        }
    }

    /**
     * A departure event
     */
    public void handleEvent(SimEvent event) {
        SimEvent finished = (SimEvent)customerQueue.removeFirst();

        double sysTime = simControl.getTime() - finished.getTime();
        double queueTime = lastServiceStart - finished.getTime();

        customerInService = false;
        servicedCustomer++;
        sumSystemTime += sysTime;
        sumQueueTimes += queueTime;

        if( customerQueue.size() > 0 ) {
            scheduleNextDeparture();
        }
    }
```

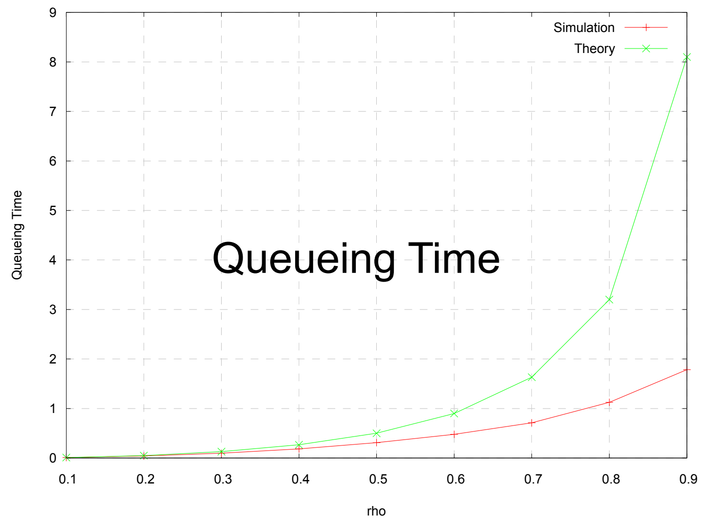
```
private void scheduleNextDeparture() {
    // The next departure will be in aServiceTime time units from now
    // That means the service starts now
    double aServiceTime = serviceTime.getNext();
    sumServiceTime += aServiceTime;
    SimEvent event = new SimEvent(this);
    event.id = servicedCustomer;
    simControl.schedule(event, aServiceTime);
    customerInService = true;
    lastServiceStart = simControl.getTime();
}

public double getMu() {
    return 1.0/getMeanServiceTime();
}
```

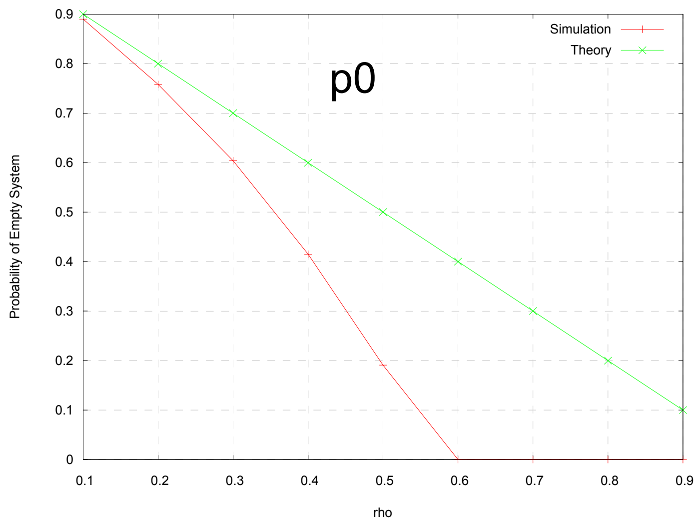
# Object-Oriented Simulation Framework

```java
public class MM1Customer {
    public static void main(String[] args) {
        System.out.println("Start");

        SimControl simulator = new SimControl(new SimLinkedList());
        simulator.setLogEvents(true);
        simulator.setRunTime(1000);

        MM1Server dst = new MM1Server(new Exponential(0.3125));
        MM1Generator src = new MM1Generator(dst, new Exponential(0.238));

        simulator.run();

        System.out.println("End");
        double lambda = 1.0/src.getLambda();
        double mu = 1.0/dst.getMu();
        double p0 =  (double)dst.getServicedCustomer() / simulator.getTime();
        double S = dst.getSystemTimes() / dst.servicedCustomer;
        System.out.println("Time        " + simulator.getTime());
        System.out.println("Arrivals    " + src.getNoOfCustomer());
        System.out.println("Serviced    " + dst.getServicedCustomer());
        System.out.println("lambda      " + lambda);
        System.out.println("mu          " + mu);
        System.out.println("rho         " + lambda/mu);
        System.out.println("p0          " + p0);
        System.out.println("S           " + S);
    }
}
```

# Object-Oriented Simulation Framework




p0 – Probability that a customer finds the system idle

## How to model discrete-event simulations?

Simulation graphs

# Simulation Graphs

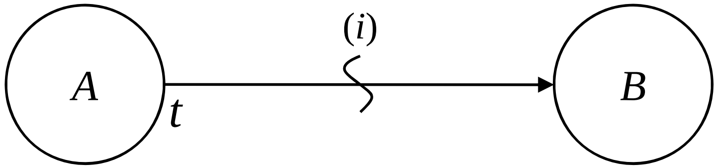
- Modeling of Discrete-Event Simulations is difficult
  - There are no standardized modeling methods
  - Modeling is something like an art ;-(

- Simulation Graphs were introduced by Schruben (1983) as Event Graphs and later renamed

- Simulation Graphs are the only graphical paradigm that directly models the Future Event List logic for a discrete-event model

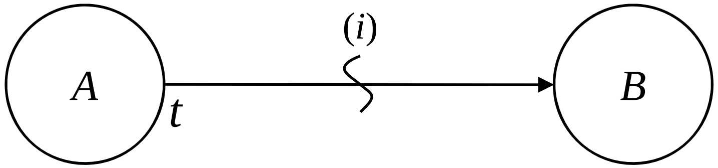
# Simulation Graphs

- A Simulation Graph consists of nodes and edges
  - Nodes: Event or state transition
  - Edges: Scheduling of events
  - Edges can have
    - Boolean condition
    - Time delay

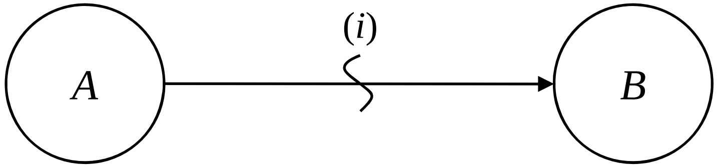


# Simulation Graphs

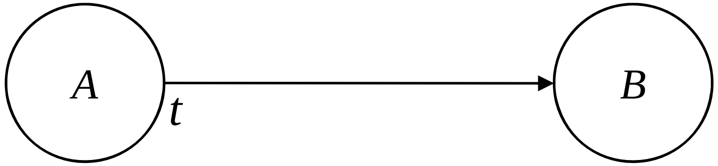
- Basic Simulation Graph
  - Event $A$ causes event $B$ to be scheduled after a time delay $t$, providing condition $(i)$ is true




  - If no time delay exists, $t$ is omitted

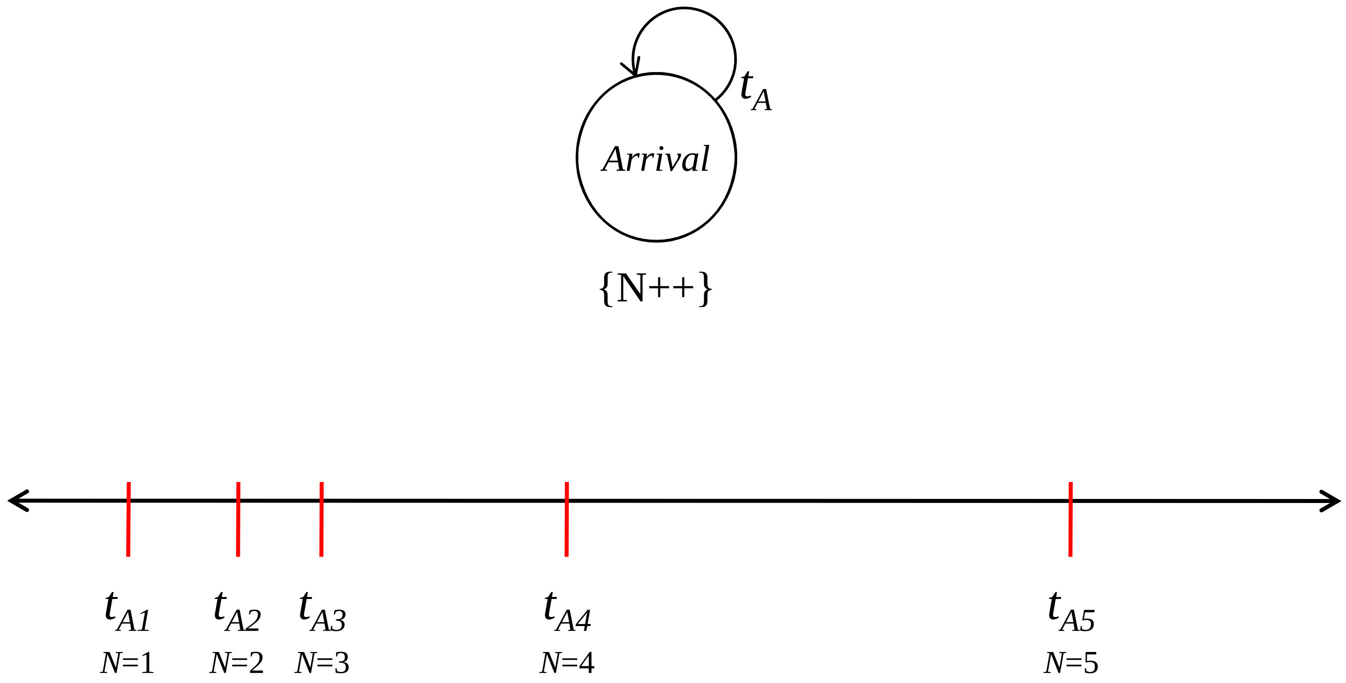



  - If event $B$ is always scheduled following the occurrence of event $A$, condition is omitted ➡ unconditional edge



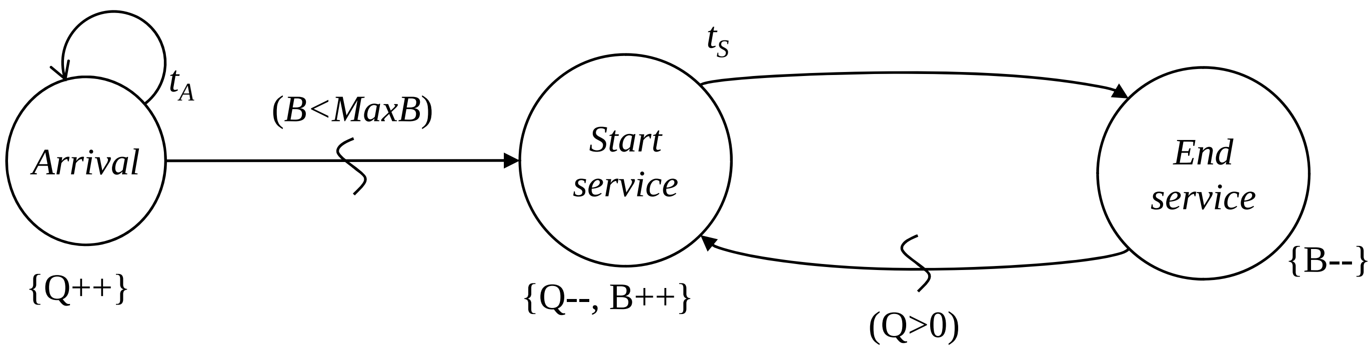
# Simulation Graphs: Poisson Process

- A Poisson process counts the number of events in a time interval
  - $N$ denotes the cumulative number of arrivals
  - $t_A$ is exponentially distributed



# Simulation Graphs: Simple Queueing

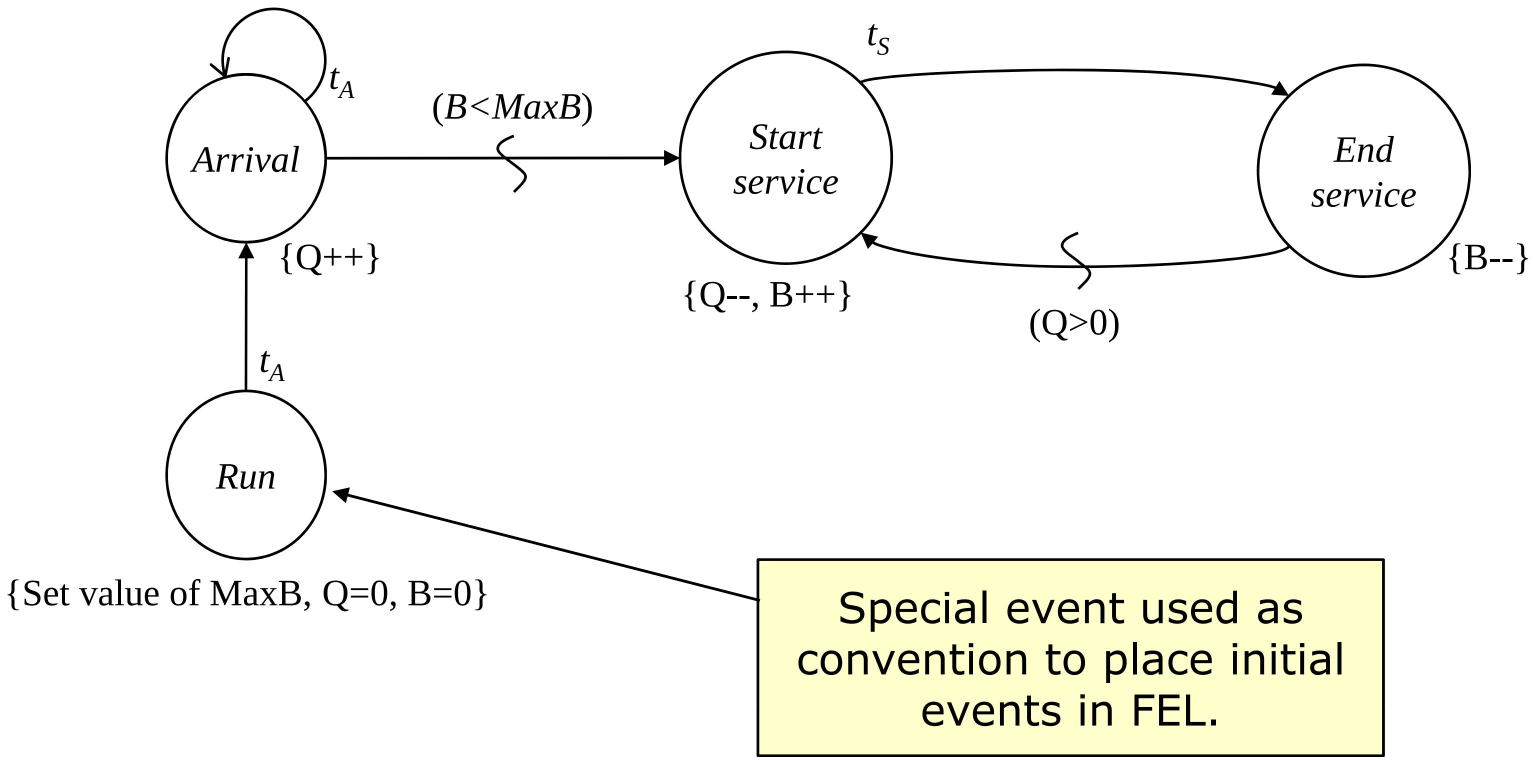
- Simple Queueing Model G/G/MaxB
  - $t_A$ Interarrival time of customer
  - $Q$ Number of customers in queue
  - $B$ Number of busy servers
  - $t_S$ Service time



# Simulation Graphs:Simple Queueing

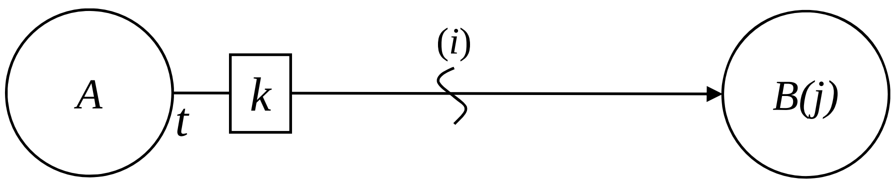
- Example yet not complete
- How to start simulation run? Initialization is open.
- Initialization consists of:
  - Setting of all parameters
  - Setting of initial values of state variables
  - Placing initial event notices
- How to determine initial events?
- With Simulation Graphs
  - Every event that has only incoming or self-scheduling edges must be scheduled at the beginning of the run.
  - As convention a special event is placed in the future event list: Run

# Simulation Graphs: Simple Queueing



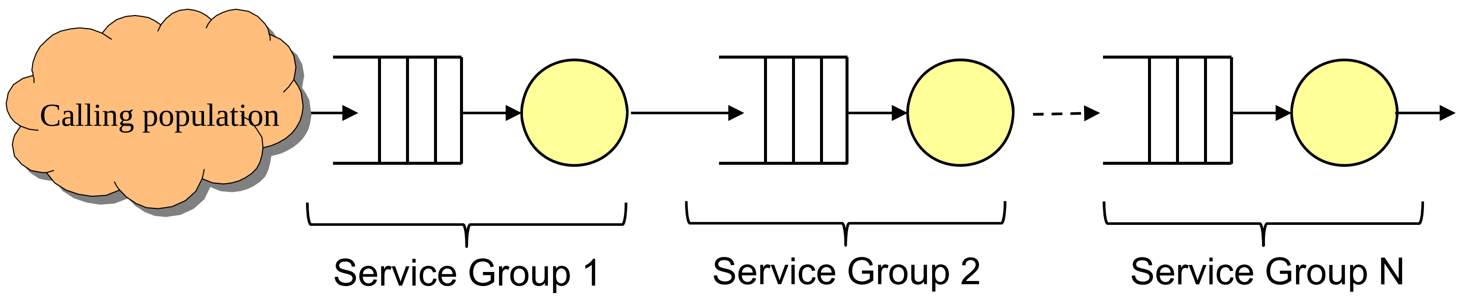
# Simulation Graphs: Passing Attributes on Edges

- Enhancement to pass attributes on edges
  - Event $A$ causes event $B$ to be scheduled after a time delay $t$, providing condition $(i)$ is true. The parameter $j$ is set to $k$.
  - Passed parameter $k$ can be a list of parameters.



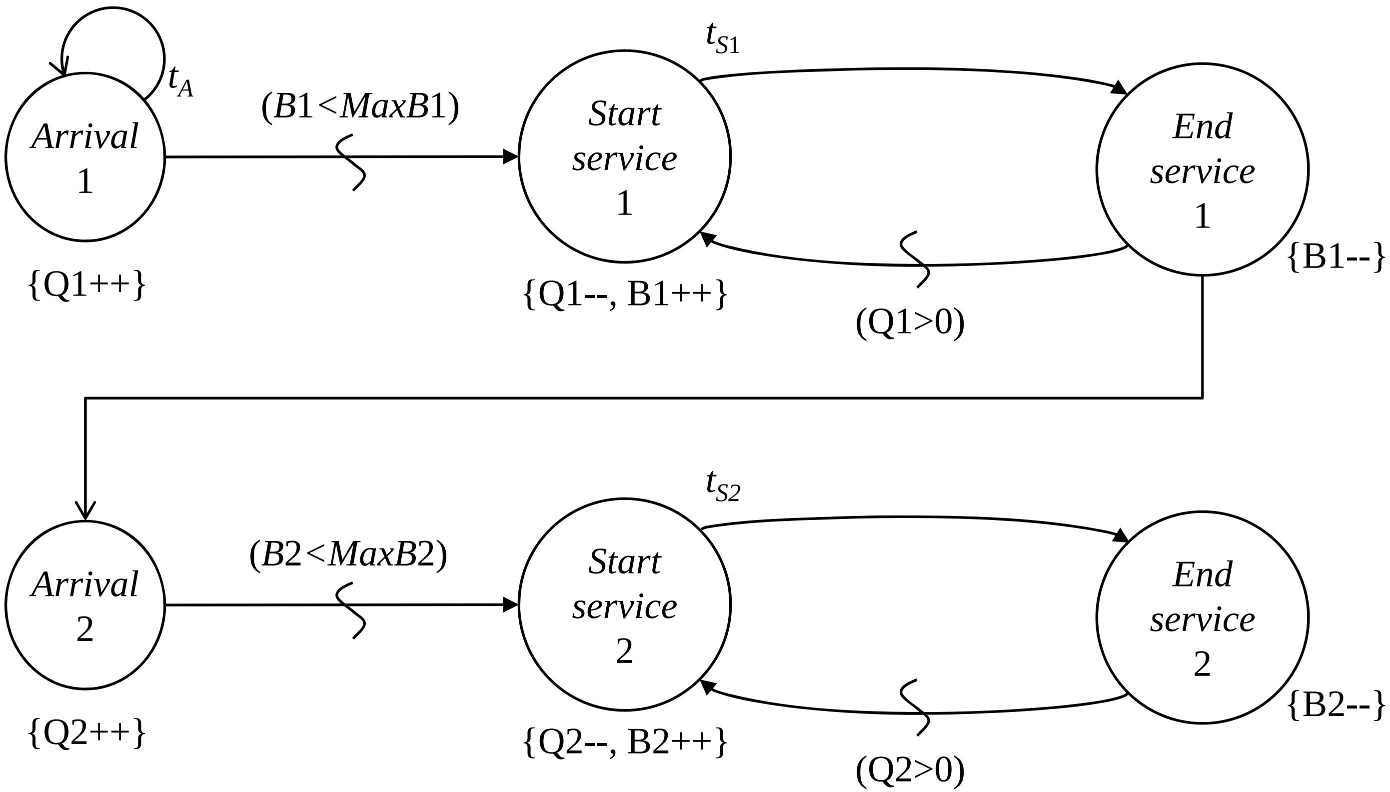
# Simulation Graphs: Series of queues

- Serie of queues consisting of N separate queues
  - Production line
  - Chain of devices



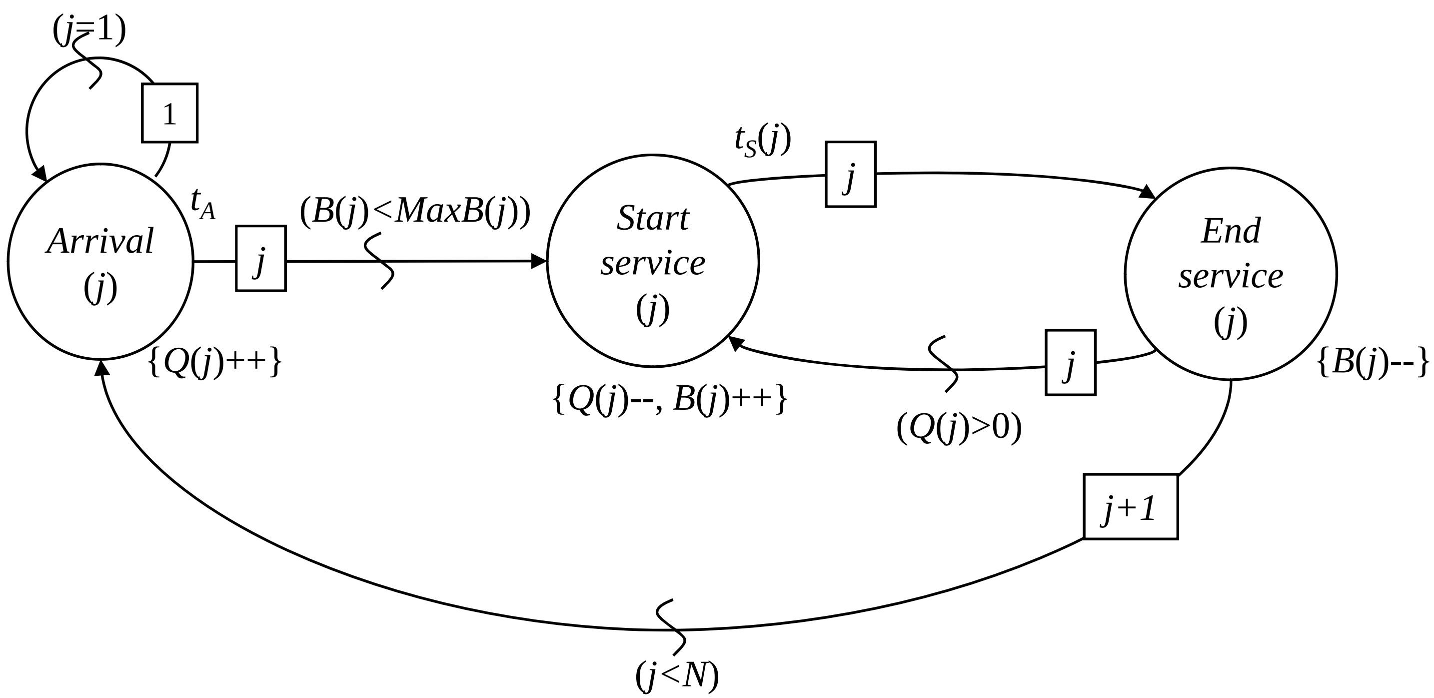
# Simulation Graphs: Series of queues

- Approach 1
  - Chain several representations of a queue



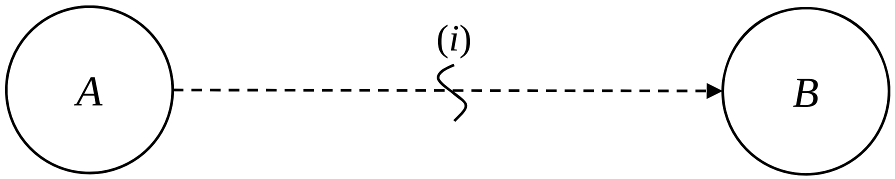
# Simulation Graphs: Series of queues

- Approach 2
  - Use edge attributes
  - The simulation code of each service station is the same



# Simulation Graphs: Canceling Edges

- Enhancement to cancel event notices from FEL
  - When event $A$ occurs and condition $(i)$ is true, the next occurrence of event $B$ is removed from the event list
  - If no event notice for $B$ is on the event list, nothing happens.



# Simulation Graphs: Summary

- Simulation Graphs
  - Simple approach to model discrete-event system
  - Allows identification of required events of simulation system
  - Graphical representation of the relationship of events
  - Enhancements allow construction of more complex models from simple ones
  - Provides optimization of simulation graphs (not discussed)

  - Disadvantage:
    - Focus is on events, modeler has to abstract from entities

# Summary

- Introduced a general framework for discrete-event simulations
- Event-scheduling and time-advance algorithm
- Generation of events
- World views for discrete simulations
- Introduced manual discrete event simulation
- Introduced simulation in Java
- Object-oriented simulation framework in Java
- Introduced Simulation Graphs as a tool to model discrete-event simulations