ECE 358: Computer Networks

Lab 1

Queue Simulation
Part 1

Presented by Hamidreza Nafissi
Based on original slides by Albert Wasef

Lab General Information

- **Lab Instructor:** Hamidreza Nafissi (*hnafissi@uwaterloo.ca*).
- **Lab TAs:**
  - **Ara Shaverdian (*ashaverdian@uwaterloo.ca*)**
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- **Communication through Piazza or email**

ECE358.F23 Lab TA Office hours					
	Mo	Tu	We	Th	Fr
12:00 - 1:00		Ara	Ara	Ara	
5:00- 6:00	Ursula	Ursula			Ursula
6:00 - 7:00	Likhil	Likhil	Likhil		

Lab General Information

- There will be 3 labs that will be done by students in groups of two:
  - LAB1: Development of a simulator of a single transmission system (weight 40%)
  - LAB 2: Development of a simulator for a CSMA/CD network (Weight 40%)
  - LAB 3: Encapsulation and network utility tools. Weight (20%)

- The total weight for the lab is dependent to your final exam mark. More details in the course outline.

Lab General Information

- Submission due dates:
  - Lab 1: Oct 6th by 11:59 pm
  - Lab 2: Nov 10th by11:59 pm
  - Lab 3: Nov 24th by11:59 pm.
- All submissions will be to the drop boxes on LEARN.
- Late lab reports will be scored a zero.
- Note that we will be analyzing submissions using Turnitin® to prevent plagiarism.

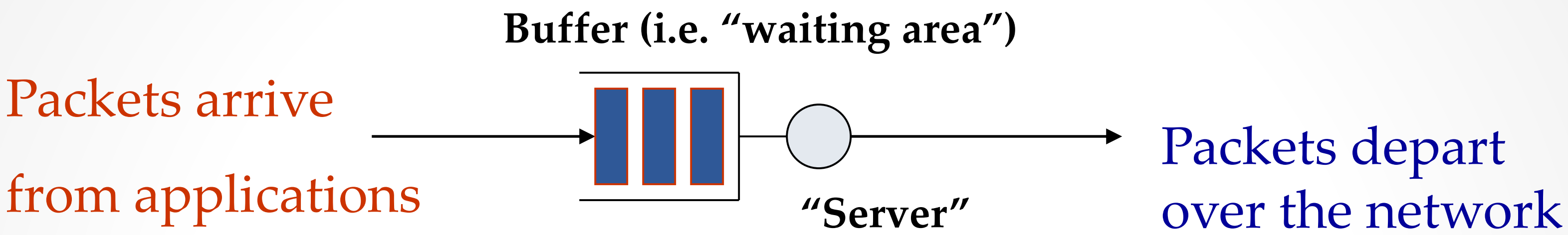
Introduction

- On any given *node* in a network, there will be one or more applications that generate a *stream* of data
- The stream is broken up into individual *packets*, which are sent out over the lower-level network interface
- The low-level interface can only send packets at a certain maximum rate
- Applications tend to generate data in bursts
- What to do when packets arrive faster than they can be sent out?

Buffering

- If packets are generated faster than they can be sent, they must be held in a *buffer*
- In practice, all buffers have a limited size (though in modern systems, this can be very large)
- If a buffer fills up, packets are discarded and must later be retransmitted
- Buffers are typically implemented as *queues* of packets

Queue Model



Single Server Queuing Model

- The "server" is usually the transmission hardware
- Analogous to a bank teller or movie-theatre cashier
- There can be multiple tellers or clerks, or just one
- **The arrival times and the service times are random**

Movie Theatre Analogy

- People (packets) don't arrive at the theatre (network node) all at once, but with random delays in between
- There is a line-up (buffer) to get to the cashier (server)
- There may be one or more cashiers available
- The length of time someone is at the cashier varies randomly depending on whether they want popcorn, drinks, candies, etc.
- When someone has gotten what they need, they exit (are transmitted) and the next person (packet) from the line-up (buffer) comes forward
- If the line-up is too long, people leave (i.e. packets are dropped) and may try again later

Main features of a queuing system

- **Arrival Process**: **Stochastic process** formed by packet arrivals (e.g., Poisson, Bernoulli, etc.).
- **Service Time**: **Random variable** denoting how long a packet will remain in service. Directly related to the length of a packet (which is why we treat as a random variable, since packets vary in size).
- **Number of Servers**.
- **Buffer Size.**
- **Service Discipline**: First in First Out (FIFO); Last in First Out (LIFO); Static priority, etc.

Kendall Notation

- Queues are typically described using a notation of the form: **A/S/C/K/D**
- Here **A** corresponds to the *arrival process* of the packets (more precisely the distribution of the inter-arrival time between packets). **λ** is the average number of packets per unit time. **A** can be M (Markovian), D (deterministic) or G (General).
- **S** corresponds to the *server process* for the packets. **S** can again be M, D or G.
- **C** corresponds to the *number of servers* (or network interfaces).
- **K** corresponds to the *buffer size*, i.e. the number of packets that can be accommodated in the "waiting room". If omitted, the buffer is assumed to be infinitely large.
- **D** corresponds to the *queueing discipline*, which is almost always FIFO and is therefore often omitted from the notation.

Kendall Notation

- Usually when a queue has infinite buffers, we drop the buffer size notation and service discipline and simply write: **A/S/C**
- Examples:

  M/M/1/10 means Markovian arrivals, exponential service time, single server, 10-packet queue

  M/D/1 means Markovian arrivals, Deterministic service time, single server, infinite queue
- In this lab, we'll be looking at M/M/1 and M/M/1/K queues
- Note that a "Markovian" process means that it follows a **Poisson distribution**, which means the *time between successive arrivals follows an exponential distribution*

Lab 1 Objectives

- Become familiar with the basic elements of **discrete event simulation**. In particular, the notion of an *event scheduler* for simulating discrete event systems
- How to generate **random variables** for a given distribution (e.g. exponential).
- The behavior of a **single buffer queue** with different parameters, which is a key element of a computer network.
- The need to be careful about **when a system should be observed**, in order to obtain valid performance metrics.

Why Simulation?

- Modern operating systems hide much of the low-level complexity of networking, and therefore make it difficult to study it at a low level
- Large networks may involve hundreds or thousands of nodes, which makes it cost-prohibitive for the *prototype implementation* model, meaning to build a prototype system just for testing and analysis
- Simulators allow us to easily adjust and tune various system parameters and observe the results

Simulation Basics

- In general, a simulation model consists of three elements:
  - Input variables (according to some statistical distribution)
  - Simulator (mathematical/logical relationship between input and output)
  - Output variables (used to estimate the performance measures of the system)

Simulation basics

- When simulating a system, you will often need to generate input variables with different distributions from a uniform random variable
- If you need to generate a random variable *X* with a distribution function F(x), you need to do the following:
  1. Generate $U \sim U(0,1)$ (Uniform random variable)
  2. Return $X = F^{-1}(U)$ where $F^{-1}(U)$ is the inverse of the distribution function of the desired random variable.
- In this lab you need to generate exponentially distributed random variables that will be used to determine when the next packet will arrive from the application or when an observation should be made.
- Recall that an exponential distribution is $F(x) = 1 - e^{-\lambda x}$

Two Possible Approaches

- Two ways to run the simulation:
  1. You can simulate the system "**tick by tick**", i.e. choose a tick resolution and advance time by that amount each time you go through a loop
     - Advantages: simple to implement, requires less memory
  2. You can maintain **a queue of events** and iterate through it
     - Advantages: runs a *lot* faster
- With tick-by-tick, a high tick resolution and a long simulation time can lead to insanely long execution times
- You can use either approach, but using tick-by-tick and leaving your project until close to the deadline is a recipe for failure

Tick-by-tick Implemetation

```
// TICKS is an integer constant that
// represents the duration of the simulation
// The duration to simulate = TICKS * tick_duration
// where tick_duration is the length of a tick

for (int i = 0; i < TICKS; ++i) {
  packet_generator(i);  // maybe generate a new packet
  server(i);  // see if current packet is done, and dequeue it
}
```

For the rest of this presentation, we'll look at the event queue implementation.

Simulator design

- Discrete event simulator (DES)
  - one of the basic paradigms for simulator design
  - used in problems where the system evolves in time, and the *state* of the system changes at discrete points in time when some *events* happen.
  - we don't need to simulate every tick of the system, since by definition nothing happens between events

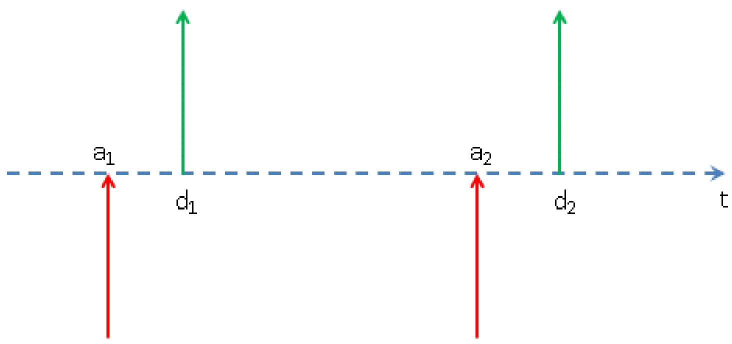
- DES is suitable for the simulation of queues
  - **State:** e.g. number of packets in the system
  - **Typical Events:**
    - Packet arrival
    - Packet departure

Performance Measures

- We are interested in measuring the following parameters:
  - The time-average number of packets in the queue, E[N],
  - The proportion of time the server is idle (i.e., the queue is empty), P_{IDLE}
  - In the case of a finite queue, the probability that a packet will be dropped due to the buffer being full when it arrives.
- When should we record the state of the system?
- The measurement and recording of the state should have **statistically representative** information on the performance that we are interested in.

The need for another event

- Consider a D/D/1



- What do we see if we look at the system at only arrival and departure times (a_1, d_1,a_2,d_2,…)?
- Need an **observer** event: an event that happens at random times, *independent* of other events
- We again use a Poisson distribution
- The simulation will now contain *three* types of events: packet arrival, packet departure, and observer

DES for a simple queue M/M/1

- Discrete event scheduler (DES) or in short Event Scheduler (ES):
  - The *ES* contains a sequence of time-ordered events E_i, $i=1,\ldots, N$, such that $t(E_i)<t(E_{i+1})$ for all i along with the time of their occurrences.

E_i	$t(E_i)$
E_{i+1}	$t(E_{i+1})$
E_{i+2}	$t(E_{i+2})$
E_{i+3}	$t(E_{i+3})$

  - Note that in the first part of this lab, ES for M/M/1 queue can be populated completely ahead of time. This is not always possible, as we'll see later.

DES Simulation Initialization

- In order to create a DES for a simple M/M/1 queue with an infinite buffer, you should do the following:

Discrete Event Simulator (DES)

Event	Time
Observer	0.0104
Observer	0.016
Observer	0.0442
Observer	0.0816
Observer	0.0946
Observer	0.1069
Observer	0.1211
Observer	0.1245

- Choose a duration T for your simulation (see later how to choose T).
- Generate a set of random observation times according to a Poisson distribution (i.e., exponential inter-arrival times) with parameter α and record the observer event times in the ES. HINT: The rate should be at least five times the rate of arrival events.

DES Simulation Initialization

- Generate a set of packet arrivals (according to a Poisson distribution with parameter λ) and their corresponding length (according to an exponential distribution with parameter 1/L), and the corresponding service time.

- Calculate their departure times based on the state of the system (the departure time of a packet of length L_p depends on how much it has to wait and on its service time L_p/C where C is the link rate).

Event	Time	Length (bits)	Service Time	Departure
Arrival	0.0135	1614	0.0016	0.015071
Arrival	0.0499	30981	0.031	0.08085
Arrival	0.0685	4487	0.0045	0.085337
Arrival	0.0815	6693	0.0067	0.088157
Arrival	0.0925	16592	0.0166	0.109135
Arrival	0.1325	56.81	6E-05	0.132512
Arrival	0.1537	21037	0.021	0.174745
Arrival	0.1597	10904	0.0109	0.185649

DES Simulation Initialization

- Populate the Discrete Event Scheduler (DES) with the observation, arrival and departure times and then sort the DES according to the timing.
- You can use arrays or linked lists or any other data structure you like. If you use arrays, sort them.
- If you use arrays, it should look like this:

Before Sorting

Arrival	0.065633411
Arrival	0.087665212
Arrival	0.120001212
Arrival	0.145761228
Arrival	0.187517327
Arrival	0.20225649
Arrival	0.251937076
Arrival	0.264276402
Departure	0.092050945
Departure	0.09386122
Departure	0.124291617
Departure	0.155661949
Departure	0.201689653
Departure	0.227061173
Departure	0.258413235
Departure	0.296843715
Observer	0.006593814
Observer	0.007847576
Observer	0.0192310011
Observer	0.024443005
Observer	0.034910443
Observer	0.059539353
Observer	0.074816364

After Sorting

Observer	0.034910443
Observer	0.059539353
Arrival	0.065633411
Observer	0.074816364
Arrival	0.087665212
Departure	0.092050945
Departure	0.09386122
Observer	0.095019652
Observer	0.101452866
Observer	0.108010377
Observer	0.11618913
Observer	0.117902974
Arrival	0.120001212
Departure	0.124291617
Observer	0.143199194
Arrival	0.145761228
Observer	0.149535313
Departure	0.155661949
Observer	0.157701614
Observer	0.166385588
Observer	0.175330675
Arrival	0.187517327
Departure	0.201689653

DES Simulation Initialization

- Initialize the following variables to zero: N_a = number of packet arrivals, N_d = number of packets departures, N_o = number of observations and idle counter

N_a
number of arrivals

N_d
number of departures

N_o
number of observations

Idle counter

Initialize all counters to Zero

DES Simulation (processing events)

- Dequeue one event at a time from your event scheduler (i.e., read one event at a time from the ES, starting with the first in the list), and call the corresponding *event procedure*. Each event procedure (one per type of event) will consist of updating some variables.

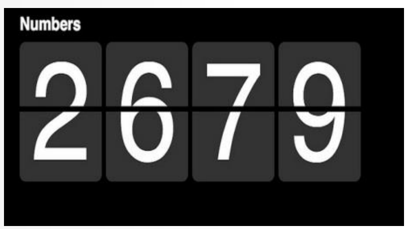
Observer	0.034910443
Observer	0.039539353
Arrival	0.065633411
Observer	0.074816364
Arrival	0.087665212
Departure	0.092050945
Departure	0.09386122
Observer	0.095019652
Observer	0.101452866
Observer	0.108010377
Observer	0.11618913
Observer	0.117902974
Arrival	0.120001212
Departure	0.124291617
Observer	0.143199194
Arrival	0.145761228
Observer	0.149535313
Departure	0.155661949
Observer	0.157701614
Observer	0.166385588
Observer	0.175330675
Arrival	0.187517327
Departure	0.201689653

Dequeue the first event in the DES

DES Simulation (processing events)

- If the event is Arrival

N_a
number of arrivals



N_d
number of departures

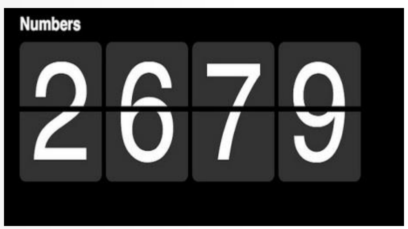
N_o
number of observations

Which counter should be updated?

DES Simulation (processing events)

- If the event is Departure

N_a
number of arrivals



N_d
number of departures

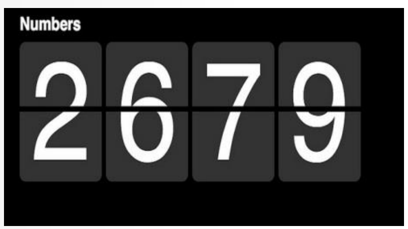
N_o
number of observations

Which counter should be updated?

DES Simulation (processing events)

- If the event is Observer

N_a
number of arrivals



N_d
number of departures

N_o
number of observations

Which counter should be updated?

DES Simulation (processing events)

- **If the event is Observer**
- Record the values of your performance metrics.
  - The number of packets in the queue
  - If the queue is empty, increment the idle counter

Idle counter

DES Simulation (processing events)

- After processing the event, delete the event from the DES

Observer	0.034910443
Observer	0.059539353
Arrival	0.065633411
Observer	0.074816364
Arrival	0.087665212
Departure	0.092050945
Departure	0.09386122
Observer	0.095019652
Observer	0.101452866
Observer	0.108010377
Observer	0.11618913
Observer	0.117902974
Arrival	0.120001212
Departure	0.124291617
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Arrival	0.145761228
Observer	0.149535313
Departure	0.155661949
Observer	0.157701614
Observer	0.166385588
Observer	0.175330675
Arrival	0.187517327
Departure	0.201689653

Delete the processed event from the DES

- Process the next event and repeat the same procedures as in the previous slides until you finish all the events in the DES

DES Simulation (calculating parameters)

- After the simulation is finished, calculate…
  - The time-average number of packets in the queue, E[N].
  - The proportion of time the server is idle (i.e., the system is empty), P_{IDLE}.

DES Simulation Initialization for M/M/1/N

DES Simulation Initialization for M/M/1/N

- Note that an ES for M/M/1/N queue **cannot** be created completely ahead of time.

- In order to create a DES for a simple M/M/1/N queue with a finite buffer, you should do the following:

  - Choose a duration T for your simulation (check for consistent results).

  - Generate a set of random observation times according to a Poisson distribution (i.e., exponential inter-arrival times) with parameter a and record the observer event times in the ES.

Discrete Event Simulator (DES)

Event	Time
Observer	0.0104
Observer	0.016
Observer	0.0442
Observer	0.0816
Observer	0.0946
Observer	0.1069
Observer	0.1211
Observer	0.1245

DES Simulation Initialization

- Generate a set of packet arrivals (according to a Poisson distribution with parameter λ)
- Note that you **cannot** generate the departure time based on the arrival time only.
- You will have to generate the departure time *on the fly* during the simulation

Event	Time
Arrival	0.065633
Arrival	0.087665
Arrival	0.120001
Arrival	0.145761
Arrival	0.187517
Arrival	0.202256
Arrival	0.251937
Arrival	0.264276

DES Simulation Initialization

- Populate the Discrete Event Scheduler (DES) with the observation and arrival times and then sort the DES according to the timing.
- It should look like this:

Before Sorting

Event	Time
Arrival	0.065633
Arrival	0.087665
Arrival	0.120001
Arrival	0.145761
Arrival	0.187517
Arrival	0.202256
Arrival	0.251937
Arrival	0.264276
Observer	0.006594
Observer	0.007848
Observer	0.019231
Observer	0.024443
Observer	0.03491
Observer	0.059539
Observer	0.074816
Observer	0.09502

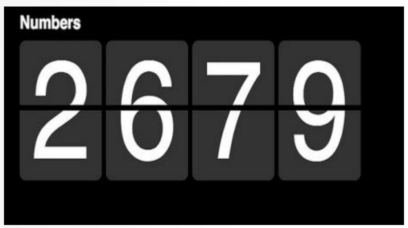
After Sorting

Observer	0.03491
Observer	0.059539
Arrival	0.065633
Observer	0.074816
Arrival	0.087665
Observer	0.09502
Observer	0.101453
Observer	0.10801
Observer	0.116189
Observer	0.117903
Arrival	0.120001
Observer	0.143199
Arrival	0.145761
Observer	0.149535
Observer	0.157702

DES Simulation Initialization

- Initialize the following counters

N_a
number of arrivals



N_d
number of departures

N_o
number of observations

Idle counter

Number of dropped packets

Number of generated packets

Initialize all counters to Zero

DES Simulation (processing events)

- Dequeue one event at a time from your event scheduler (i.e., read one event at a time from the ES, starting with the first in the list), and call the corresponding *event procedure*. Each event procedure (one per type of event) will consist of updating some of variables.

Observer	0.03491
Observer	0.059539
Arrival	0.065633
Observer	0.074816
Arrival	0.087665
Observer	0.09502
Observer	0.101453
Observer	0.10801
Observer	0.116189
Observer	0.117903
Arrival	0.120001
Observer	0.143199
Arrival	0.145761
Observer	0.149535
Observer	0.157702

Dequeue the first event in the DES

DES Simulation (processing events (Arrival))

- **If the event is Arrival**
- Check how many packets are in the queue:
  - If the buffer is full, drop the packet and increment the appropriate counter(s).

N_a
number of arrivals

N_d
number of departures

N_o
number of observations

Idle counter

Number of dropped packets

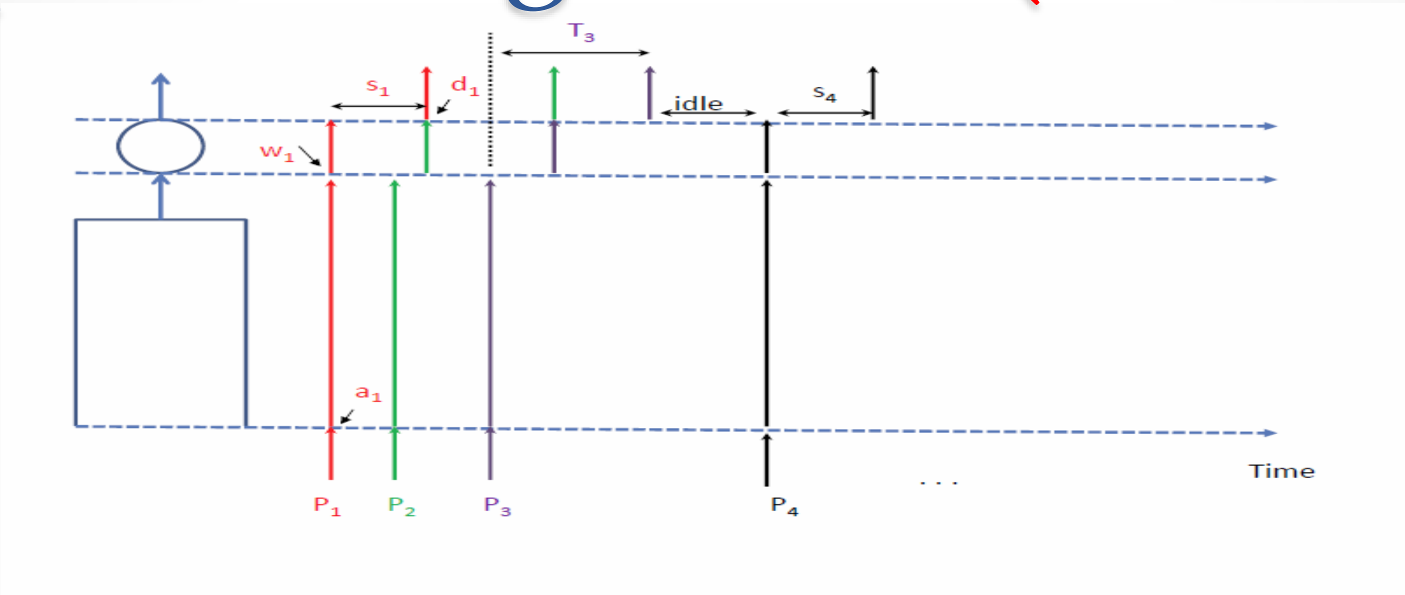
Number of generated packets

Which counter(s) should be updated?

DES Simulation (processing events (Arrival))

- Otherwise (i.e., the queue is either empty or partially filled)
  - Generate a length for the arriving packet (according to an exponential distribution with parameter 1/L), and compute the corresponding service time.
  - Calculate the departure time (of the packet which just arrived in the system) based on the state of the system (the departure time of a packet of length L_p depends on how much it has to wait and on its service time L_p/C where C is the link rate).

DES Simulation (processing events (Arrival))

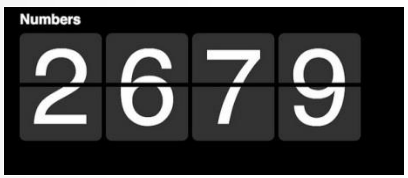


- Compute the departure time of the packet
  - If queue is empty, it's just arrival time + service time
  - What if it's not? (you need to think about this)
- Insert packet into DES in the correct place based on its departure time

DES Simulation (processing events (Departure))

- If the event is Departure

N_a
number of arrivals



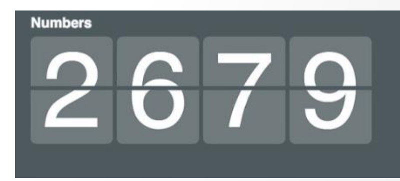
N_d
number of departures

N_o
number of observations

Idle counter

Number of dropped packets

Number of generated packets

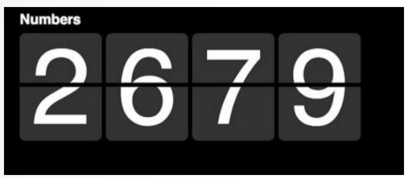


Which counter(s) should be updated?

DES Simulation (processing events (Observer))

- If the event is Observer

N_a
number of arrivals



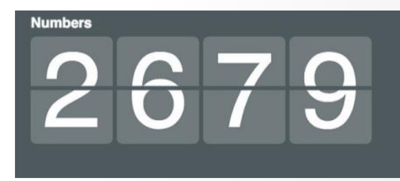
N_d
number of departures

N_o
number of observations

Idle counter

Number of dropped packets

Number of generated packets



Which counter(s) should be updated?

DES Simulation (processing events (Observer))

- **If the event is Observer**
- Record the values of your performance metrics.

  - The number of packets in the queue.

  - If the queue is empty, increment the idle counter

Idle counter

DES Simulation (processing events)

- After processing the event, delete the event from the DES

Observer	0.03491
Observer	0.059539
Arrival	0.065633
Observer	0.074816
Arrival	0.087665
Departure	0.092051
Observer	0.09502
Observer	0.101453
Observer	0.10801
Observer	0.116189
Observer	0.117903
Arrival	0.120001
Observer	0.143199
Arrival	0.145761
Observer	0.149535
Observer	0.157702

Delete the processed event from the DES

- Process the next event and repeat the same procedures as in the previous slides until you finish all the events in the DES

DES Simulation (calculating parameters)

- After the simulation is finished, calculate…

➢ The time-average number of packets in the queue, E[N].

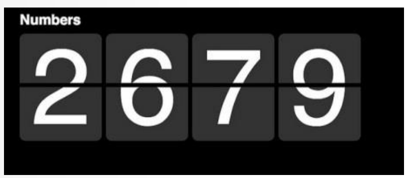
➢ The proportion of time the server is idle (i.e., the system is empty), P_{IDLE}.

➢ The probability that a packet will be dropped, P_{LOSS}.

DES Simulation (calculating parameters)

Use the final counter values to compute the various values

N_a
number of arrivals



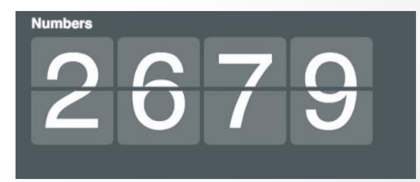
N_d
number of departures

N_o
number of observations

Idle counter

Number of dropped packets

Number of generated packets



DES Simulation (simulation time)

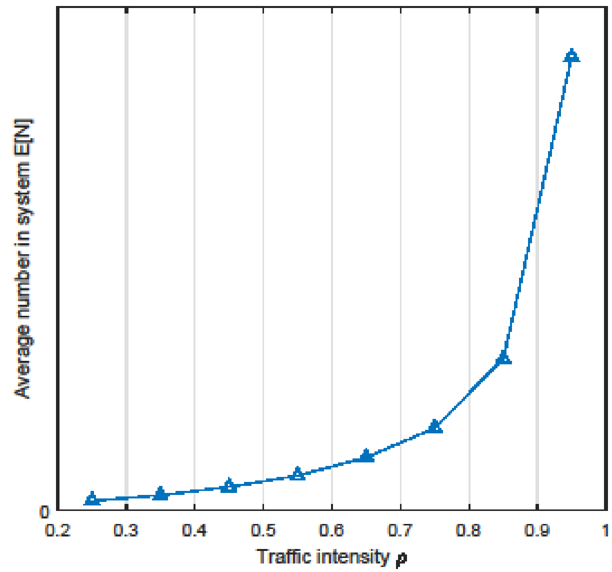
- Initially choose T = 1000 seconds (simulated time, not actual wall-clock time)
- Run each experiment in this lab for T seconds and record the result. Then run the experiment again for 2T seconds and see if the expected values of the output variables are similar to the output from the previous run, i.e., the difference is less than 5%. If the results are not similar, keep increasing T until we get stable results.
- Note that this should be done for every experiment.
- If you do not indicate this time checking procedure in your report, you will lose marks.

What is rho (ρ)

- ρ is the *queue utilization* or "traffic intensity", defined as **the input rate divided by the service rate**
- Input rate is λ
- Service time is L / C
- Service rate is C / L (inverse of the service time)
- So $\rho = \lambda / (C/L) = \lambda L / C$
- In this lab, you'll be given L and C and will vary ρ over some range to compute a series of λ values

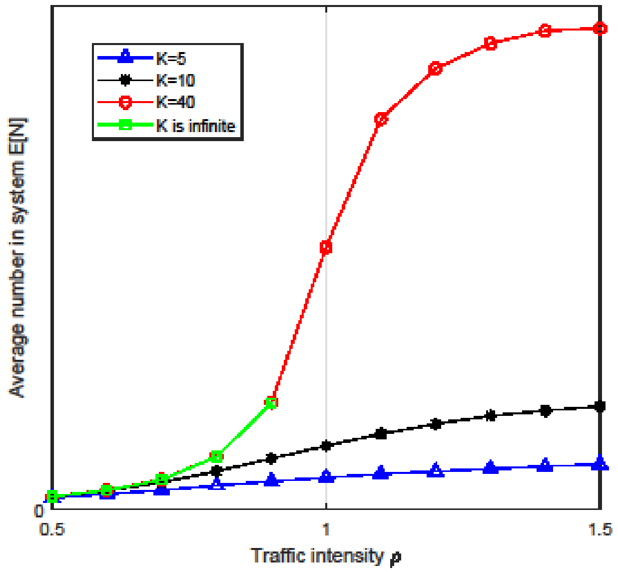
Expected Graph for Question 3

- Your graph should look something like this:



Expected Graph for Question 6

- Your graph should look something like this:



Notes

- Programming languages: you can use C, C++ , Python, Java or any other programming language that is available on eceUbuntu
- Your code must compile and run on the eceUbuntu servers since that's where the TAs will be testing it
- You must submit your code and your report on Learn
- You should submit your files individually, not in a zip or tar file
- You should provide a single command that builds and runs your application and describe how to use it

Questions?