CSE 400: Project Scribe Report – Questions 1–3

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Scribe Question 1: Project System and Objective

The main probabilistic problem in our project is to understand why and how packet delay happens in a single router network when traffic is random. In real communication systems such as video streaming, online gaming, and cloud services, data is sent in the form of packets. These packets do not arrive at the router at fixed or predictable times. Sometimes many packets arrive together, and sometimes very few packets arrive. Because of this randomness, congestion can occur at the router, which causes packets to wait and experience delay.

Our project mainly focuses on studying packet delay using probability, instead of trying to predict exact arrival times. Since real network traffic depends on human behaviour and application usage, it cannot be modeled with certainty. Therefore, packet delay must be treated as a random quantity.

The system we consider consists of a single router with a buffer (queue). Packets arrive from multiple independent sources and enter the router. If the router is busy processing another packet, incoming packets wait in the queue. The router processes packets one at a time, and after processing, packets leave the system. This simple system allows us to study the main causes of delay without adding unnecessary complexity.

The objective of our project is not to design or improve router hardware, but to analyze and quantify packet delay under uncertainty. Specifically, the objectives are:

- To estimate the average packet delay experienced by packets
- To study how random traffic patterns affect queue length and waiting time
- To apply queueing theory and probabilistic reasoning to understand congestion behavior

The main sources of uncertainty in the system are:

- Random packet arrivals, because users send data at unpredictable times
- Variable service time, since packets have different sizes and require different processing times

- Resource contention, because multiple packets compete for a single processing unit at the router.
- Due to these uncertainties, packet delay cannot be predicted deterministically and must be studied using probablistic models.

These factors make packet delay an inherently probabilistic phenomenon, which is why probability-based models are required to study the system.

Scribe Question 2: Key Random Variables and Uncertainty Modeling

To represent uncertainty in the router system, we define several key random variables, each describing a different part of the packet flow.

Inter-arrival Time (A): Inter-arrival time is the time between two packet arrivals at the router. Since packets arrive randomly and independently, inter-arrival time is treated as a random variable. We assume packet arrivals follow a Poisson process, which means inter-arrival times are exponentially distributed. This is a common assumption in networking to model random arrivals.

Service Time (S): Service time is the time taken by the router to process a packet. It varies because packets are of different sizes. To capture this variability, service time is assumed to follow an exponential distribution, which makes the analysis simpler.

Packet Delay (D or W): Packet delay is the total time a packet spends in the system, including both waiting time and service time. Since arrivals and service are random, packet delay is also a random variable and depends on how many packets are already present in the queue due to earlier arrivals.

Queue Length (Q): Queue length represents the number of packets waiting in the queue at any given moment. It changes over time depending on how fast packets arrive and how fast they are processed.

To model all these variables together, we use the **M/M/1 queueing model**, which has the following characteristics:

- Packet arrivals follow a Poisson distribution with rate λ
- Service times follow an exponential distribution with rate μ
- There is one server (router)
- The buffer size is infinite
- Packet loss is not considered

These assumptions help us focus on probabilistic delay behaviour while keeping the model mathematically manageable at this stage of the project.

Scribe Question 3: Probabilistic Reasoning and Dependencies

Probabilistic reasoning in our project is used to understand how different random variables interact within the queueing system. A key assumption in the model is independence.

We assume that:

- Packet arrivals are independent of each other
- Service times are independent of arrivals and of other service times

This independence allows arrival and service processes to be analyzed separately and then combined using standard queueing theory results.

An important parameter in the system is **traffic intensity**, defined as:

$$\rho = \frac{\lambda}{\mu}$$

Traffic intensity shows how busy the router is and plays a major role in determining queue length and packet delay.

Using probabilistic reasoning, we understand that:

- If the arrival rate is less than the service rate ($\lambda < \mu$), the system is stable and average delay remains finite
- If the arrival rate is greater than or equal to the service rate ($\lambda \geq \mu$), the queue keeps growing and delays become very large

Conditional reasoning is also involved in the system. For example, the waiting time of a packet depends on how many packets are already in the queue when it arrives. Similarly, the queue length at any time depends on past arrival and service events.

By modeling these relationships probabilistically, we are able to:

- Estimate expected packet delay
- Predict average queue length
- Reason about congestion without tracking each packet individually

Overall, probabilistic reasoning allows us to move from unpredictable packet-level behavior to meaningful system-level performance measures, which is the main goal of this project.