1. (25 points) State whether the following statements are true or false. **No justification is necessary.**

   (a) (5 points) **Statement:** The superposition of two Poisson processes is a Poisson process.

   (b) (5 points) **Statement:** TCP is a transport layer congestion control protocol that does not permit packets to traverse multiple paths.

   (c) (5 points) Every packet that arrives at a network node A in time interval $(0, t)$ is transmitted to station 1 with probability 1/2 and station 2 with probability 1/2, independently of other packets. Station 1 and 2 are connected only to node A. Packets arrive at the network node A at a rate of 2 packets per second.

   Statement: Given the above configuration,

$$\lim_{t\to\infty} |N_1(t) - N_2(t)| \to \infty,$$

   where $N_i(t)$ is the number of packets that arrive at station i, $i = 1, 2$.

   (d) (5 points) **Statement:** The *Selective Repeat* protocol has not been as popularly implemented in real systems as the *Go-Back-N* protocol because of the requirement of a re-ordering buffer at the receiver.

   (e) (5 points) Consider an M/M/1 queue with arrival rate λ and service rate μ. Each departing packet from the system is sent back to the back of the queue with probability p. Assume that the queue is stable.

   Statement: The average number of packets in the system is $\rho/(1-\rho)$, where $\rho = \lambda/((1-p)\mu)$.

2. (35 points)

   (a) (15 points) Carefully describe the Dijkstra's algorithm for computing the minimum-delay path in a directed network (i.e., each edge is directed, e.g., the network in Fig. 1).

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(b) (20 points) Using the Dijkstra's algorithm, find the shortest path from node A to all other nodes in the network shown below. The number next to each edge represents its delay.

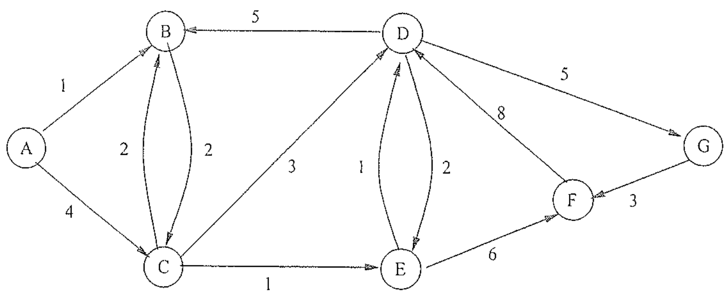

Figure 1: A directed network

3. (**40 points**) Customers arrive to a three-server system in Fig. 2 according to a Poisson process with rate λ. Each server is associated with an infinite-buffer queue. An incoming customer is routed independently to each queue with equal probability ($= 1/3$). Each queue is served in a first-come-first-serve manner. However, due to resource conflicts, the servers cannot all operate at the same time. Specifically, Server 1 and Server 3 can operate at the same time while Server 2 is idle. Alternatively, Server 2 can operate when both Server 1 and Server 3 are idle. In the first case, Server 1 and Server 3 will both operate for a common period of time that is *i.i.d.* exponentially distributed with mean $1/\mu$. At the end of the operation period, each of them can serve one customer if there is one in their respective queue. Similarly, in the latter case Server 2 will operate for an *i.i.d.* exponentially-distributed amount of time with mean $1/\mu$. At the end of the operation period, Server 2 can also serve one customer if there is one in its queue. We assume that each customer takes a negligible amount of time to serve. At any time, with 1/2 probability Servers 1 and 3 will be chosen to operate, and with 1/2 probability Server 2 will be chosen to operate. Further, after one operation period ends, the next set of server(s) to operate is again chosen independently with probability 1/2 among the two possible alternatives.

(a) (10 points) Let T_1 denote the length of the time-interval from the time that a

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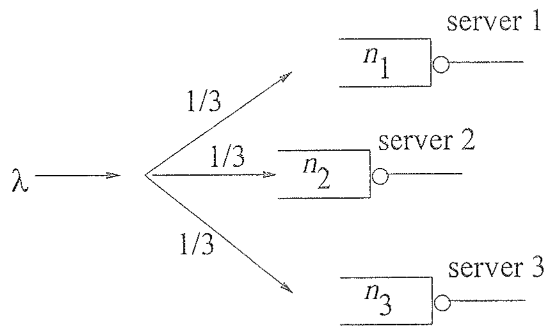

Figure 2: A three-queue system

customer becomes the first in queue 1, to the time that it is served. Show that the mean of T_1 is equal to $2/\mu$.

(b) (10 points) Draw the state-transition diagram that can be used to find P_{n_1}, the probability that there are n_1 customers in queue 1.

(c) (10 points) Find P_{n_1}.

(d) (10 points) Find $\mathbf{E}[n_1]$, i.e., the expected number of customers in queue 1.

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