

SOLUTIONS 8

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Exercise 1. A *simple birth process* $(X(t))_{t \geq 0}$ on $\{0, 1, 2, \dots\}$ is a generalisation of a Poisson process by introducing a correlation between the parameter λ and the actual state of the process. More precisely, if the process is in state i , it will go to state $i+1$ after an exponential random time of parameter $0 \leq \delta_i < \infty$. This process is also a Markov process (using similar arguments as those used to prove that a Poisson process is Markovian.)

- (i). Find the Q -matrix corresponding to the simple birth process.
- (ii). Let $X(0) = 0$ and T_i be the time when the i th jump occurs. Find an example of a simple birth process such that $\lim_{i \rightarrow \infty} T_i < \infty$ a.s. This phenomena is called "the explosion". Find a general condition on the δ_i 's so that the process explodes almost surely in a finite amount of time.
- (iii). Do we have an explosion in the Poisson process case?
- (iv). More generally, use the strong law of large numbers to show that if $\sup_{i \in \mathbb{N}} \delta_i < \infty$, then $\lim_{i \rightarrow \infty} T_i = \infty$ almost surely.

Solution. (i). The transition rates matrix Q on $\{0, 1, 2, \dots\}$ is given by

$$Q = \begin{pmatrix} -\delta_0 & \delta_0 & 0 & 0 & \cdots \\ 0 & -\delta_1 & \delta_1 & 0 & \cdots \\ 0 & 0 & -\delta_2 & \delta_2 & \ddots \\ 0 & 0 & 0 & -\delta_3 & \delta_3 \\ \vdots & \vdots & \vdots & \ddots & -\delta_4 \end{pmatrix}$$

- (ii). We let $\delta_i = (i+1)^2$ for all $i \geq 0$. We can easily verify that $\lim_{i \rightarrow \infty} T_i < \infty$ almost surely by computing its expectation:

$$\mathbb{E}[\lim_{i \rightarrow \infty} T_i] = \mathbb{E}\left[\sum_{i=1}^{\infty} (T_i - T_{i-1})\right] = \sum_{i=1}^{\infty} \delta_{i-1}^{-1} = \sum_{i=1}^{\infty} \frac{1}{i^2} < \infty.$$

Similarly, the process explodes almost surely if

$$\mathbb{E}[\lim_{i \rightarrow \infty} T_i] = \mathbb{E}\left[\sum_{i=1}^{\infty} (T_i - T_{i-1})\right] = \sum_{i=1}^{\infty} \delta_{i-1}^{-1} < \infty. \quad (1)$$

- (iii)-(iv). Let $S_{i-1} = T_i - T_{i-1}$ the waiting time between the $(i-1)$ and the i th jump, that follows an exponential law of parameter δ_{i-1} (since we start at $X_0 = 0$). It is easy to see that $\delta_i S_i$ follows an exponential law of parameter 1. By the strong law of large numbers, we obtain:

$$\frac{\sum_{i=0}^{n-1} \delta_i S_i}{n} \xrightarrow{a.s.} 1.$$

For n sufficiently large, we thus get

$$\frac{\sum_{i=0}^{n-1} \delta_i S_i}{n} > \frac{1}{2}.$$

This is equivalent to $\sum_{i=0}^{n-1} \delta_i S_i > \frac{n}{2}$ for n sufficiently large, and this implies that $\sum_{i=0}^{n-1} \delta_i S_i \rightarrow \infty$ a.s.

If $\sup_{j \in \mathbb{N}} \delta_j < \infty$, we can write

$$\sum_{i=0}^{n-1} S_i \geq \frac{1}{\sup_j \delta_j} \sum_{i=0}^{n-1} \delta_i S_i \rightarrow \infty.$$

Thus we have that $\lim_{i \rightarrow \infty} T_i = \sum_{i=1}^{\infty} (T_i - T_{i-1}) = \sum_{i=0}^{\infty} S_i = \infty$ almost surely and so the process does not explode in this case.

In particular, the Poisson process does not explode since all the δ_i 's are equal in this case (to some $\lambda < \infty$) and so we have $\sup_{j \in \mathbb{N}} \delta_j < \infty$.

We can even obtain a stronger result that shows that if the sum in (1) is infinite, then the process does not explode. (see theorem 2.3.2 in Norris)

Exercise 2. A radioactive source emits particles according to a Poisson process of rate λ . The particles are spread in random directions independently from each other. A Geiger counter placed next to the source measures a fraction p of the emitted particles. What is the distribution of the number of particles detected by time t ?

Solution. The number of emitted particles up to time t follows has a law *Poisson* (λt) . For each emitted particle, the probability that it is detected by the counter is p . Knowing that the number of emitted particles until time t is equal to n , the number of detected particles has a law *Binomial* (n, p) . We use this to obtain

$$\begin{aligned} \mathbb{P}(\# \text{ detected particles} = r) &= \sum_{n=r}^{\infty} \mathbb{P}(\# \text{ of particles} = n) \binom{n}{r} p^r (1-p)^{n-r} = \\ &= \sum_{n=r}^{\infty} e^{-\lambda t} \frac{(\lambda t)^n}{n!} \frac{n!}{r! (n-r)!} p^r (1-p)^{n-r} = \\ &= \frac{e^{-\lambda t} p^r}{r!} \sum_{n=r}^{\infty} \frac{(\lambda t)^n}{(n-r)!} (1-p)^{n-r} = \\ &= \frac{e^{-\lambda t} p^r (\lambda t)^r}{r!} \sum_{n=r}^{\infty} \frac{(\lambda t (1-p))^{n-r}}{(n-r)!} = \\ &= \frac{e^{-\lambda t} (\lambda t p)^r}{r!} \sum_{n=0}^{\infty} \frac{(\lambda t (1-p))^n}{n!} = \\ &= \frac{e^{-\lambda t} (\lambda t p)^r}{r!} e^{\lambda t (1-p)} = \\ &= e^{-\lambda t p} \frac{(p \lambda t)^r}{r!}. \end{aligned}$$

Exercise 3. The arrival times of the bus number 1 are modeled by a Poisson process with an average frequency of one bus per hour, whereas the arrival times of the bus number 7 are modeled by a Poisson process independent of the first one with frequency of 7 buses per hour.

- (1) What is the probability that we see exactly 3 buses (no matter which buses) in one hour?

- (2) What is the probability that we see exactly 3 buses 7 while we are waiting for the bus 1?

Solution. (1) By a result seen in class, we know that that buses are arriving according to a Poisson process of rate $\lambda = 1 + 7 = 8$. By exercise 1, The number of buses passing in one hour follows a Poisson distribution of mean 8. Then the probability that we see exactly 3 buses is given by $e^{-8}8^3/3!$.

- (2) Let $E_i \sim \text{Exp}(1)$ and $E'_i \sim \text{Exp}(7)$ be the waiting times between two consecutive arrivals of buses 1 and 7 respectively. The probability that the first bus is 7 is given by

$$\mathbb{P}(E'_1 < E_1) = \int_0^\infty f_{E'_1}(s) \mathbb{P}(E_1 > s) ds = \int_0^\infty 7e^{-7s} e^{-s} ds = \frac{7}{8} \int_0^\infty 8e^{-8s} ds = \frac{7}{8}.$$

Using the independence of E_1, E'_1 and E'_2 , the probability that the second bus is also the 7 is given by

$$\begin{aligned} \mathbb{P}(E_1 > E'_1 + E'_2 \mid E_1 > E'_1) &= \frac{\int_0^\infty \int_0^\infty \mathbb{P}(E_1 > s+t) f_{E'_1}(s) f_{E'_2}(t) ds dt}{\int_0^\infty \mathbb{P}(E_1 > s) f_{E'_1}(s) ds} \\ &= \frac{\int_0^\infty \int_0^\infty e^{-(s+t)} f_{E'_1}(s) f_{E'_2}(t) ds dt}{\int_0^\infty e^{-s} f_{E'_1}(s) ds} \\ &= \frac{\int_0^\infty e^{-s} f_{E'_1}(s) ds \int_0^\infty e^{-t} f_{E'_2}(t) dt}{\int_0^\infty e^{-s} f_{E'_1}(s) ds} \\ &= \int_0^\infty e^{-t} f_{E'_2}(t) dt = \mathbb{P}(E_1 > E'_2) = \frac{7}{8}. \end{aligned}$$

Following the same reasoning, The probability that the third bus is again the 7 is $\frac{7}{8}$. Letting A_i be the event "the i^{th} bus is the 7", we finally get

$$\mathbb{P}(A_1 \cap A_2 \cap A_3 \cap A_4^c) = \mathbb{P}(A_1) \cdot \mathbb{P}(A_2 \mid A_1) \cdot \mathbb{P}(A_3 \mid A_1 \cap A_2) \cdot (1 - \mathbb{P}(A_4 \mid A_1 \cap A_2 \cap A_3)) = \left(\frac{7}{8}\right)^3 \cdot \frac{1}{8}.$$

Alternative method: Let $S_n := \sum_{i=1}^n E_i$ and $S'_m := \sum_{j=1}^m E'_j$ where $E_i \sim \text{Exp}(1)$ and $E'_j \sim \text{Exp}(7)$. The probability of seeing exactly 3 buses 7 before the arrival of bus 1 is given by

$$\mathbb{P}(S'_3 \leq S_1 \leq S'_4).$$

Using that S'_3 has an Erlang distribution (see exercise 4 in Serie 7) with parameters $n = 3$ and $\lambda = 7$, we get

$$\begin{aligned} \mathbb{P}(S'_3 \leq S_1 \leq S'_4) &= \int_0^\infty \mathbb{P}(s \leq S_1 \leq s + E'_4) \frac{7^3}{2} t^2 e^{-7s} ds \\ &= \int_0^\infty \left(\int_0^\infty \mathbb{P}(s \leq E_1 \leq s+t) 7e^{-7t} dt \right) \frac{7^3}{2} t^2 e^{-7s} ds \\ &= \int_0^\infty \frac{e^{-s}}{8} \times \frac{7^3}{2} t^2 e^{-7s} ds \\ &= \int_0^\infty \frac{7^3}{16} \times t^2 e^{-8s} ds = \frac{7^3}{8^4}. \end{aligned}$$

Exercise 4. Hockey teams 1 and 2 score goals at times of Poisson processes with rates 1 and 2. Suppose that $N_1(0) = 3$ and $N_2(0) = 1$.

- a) What is the probability that $N_1(t)$ will reach 5 before $N_2(t)$ does?
 b) Answer part a) for Poisson processes with rates λ_1 and λ_2 .

Solution. a) The probability that team 2 (T_2) scores the first goal is $\frac{2}{3}$ (using the exercise 2 of serie 1). Therefore, using the memoryless property of the exponential distribution, the probability that at least 4 of the 5 next goals are scored by Team 2 is

$$\begin{aligned}\mathbb{P}(\text{Team 2 wins}) &= \mathbb{P}(T_2 \text{ scores at least 4 of the next 5 goals}) \\ &= \binom{5}{4} \left(\frac{2}{3}\right)^4 \cdot \frac{1}{3} + \binom{5}{5} \left(\frac{2}{3}\right)^5.\end{aligned}$$

Hence, the probability the Team 1 (T_1) wins is

$$\mathbb{P}(T_1 \text{ wins}) = 1 - \binom{5}{4} \left(\frac{2}{3}\right)^4 \cdot \frac{1}{3} + \binom{5}{5} \left(\frac{2}{3}\right)^5 = \frac{131}{243}.$$

Another way of computing this probability is by noticing that the waiting time for T_1 to score 2 goals has the Erlang (or Gamma) distribution with parameters 2 and 1. Likewise, the waiting time for team T_2 to score 4 goals is distributed as $\Gamma(4, 2)$. Therefore, the probability that we are looking for is given by

$$\mathbb{P}(\Gamma(2, 1) \leq \Gamma(4, 2)) = \int_0^\infty t e^{-t} \left(\int_t^\infty \frac{2e^{-2s}(2s)^3}{6} ds \right) dt.$$

After some computations, we get

$$\mathbb{P}(T_1 \text{ wins}) = \mathbb{P}(\Gamma(2, 1) \leq \Gamma(4, 2)) = \int_0^\infty e^{-3t} \left(\frac{4}{3}t^4 + 2t^3 + 2t^2 + 3t \right) dt = \frac{131}{243}.$$

- b) Similarly to part a), the probability that T_1 wins is

$$\mathbb{P}(T_1 \text{ wins}) = 1 - 5 \left(\frac{\lambda_2}{\lambda_1 + \lambda_2} \right)^4 \frac{\lambda_1}{\lambda_1 + \lambda_2} - \left(\frac{\lambda_2}{\lambda_1 + \lambda_2} \right)^5.$$