

Introduction

Schedule:

- (I) Basic properties of continuous-time Markov Chains
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- (IV) Renewal theory
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1 Some basic aspects of continuous-time Markov Chains

Definition. A sequence of random variables is called a *stochastic process* or *process*. The process $X = (X_n)_{n \geq 1}$ is called a discrete-time Markov Chain with state space I if for all $x_0, x_1, \dots, x_n \in I$

$$\mathbb{P}(X_n = x_n | X_{n-1} = x_{n-1}, \dots, X_0 = x_0) = \mathbb{P}(X_n = x_n | X_{n-1} = x_{n-1}).$$

If $\mathbb{P}(X_{n+1} = y | X_n = x)$ is independent of n , the chain is called *time-homogeneous*. We then write $P = (P_{x,y})_{x,y \in I}$ for the *transition matrix* where $P_{x,y} = \mathbb{P}(X_1 = y | X_0 = x)$. The data associated to every time-homogeneous Markov Chain is the transition matrix P and the initial distribution μ , i.e $\mathbb{P}(X_0 = x_0) = \mu(x_0)$.

From now on:

- I denotes a countable (or finite) state space.
- $(\Omega, \mathcal{F}, \mathbb{P})$ is the probability space on which all the relevant random variables are defined.

Definition. $X = (X(t) : t \geq 0)$ is a (right-continuous) continuous-time random process with values in I if

- (a) for all $t \geq 0$, $X(t) = X_t$ is a random variable such that $X(t) : \Omega \rightarrow I$;
- (b) for all $\omega \in \Omega$, $t \mapsto X_t(\omega)$ is right-continuous (right-continuous sample path).
In our case this means for all $\omega \in \Omega$, for all $t \geq 0$, there exists $\varepsilon > 0$ (depending on ω, t) such that

$$X_t(\omega) = X_s(\omega) \quad \forall s \in [t, t + \varepsilon].$$

Fact. A right-continuous random process is defined by its finite-dimensional distributions

$$\mathbb{P}(X_{t_0}=i, X_{t_1}=i_1, \dots, X_{t_n}=i_{t_n}), \quad n \geq 0, \quad t_k \geq 0, \quad i_k \in I.$$

For every $\omega \in \Omega$, the path $t \mapsto X_t(\omega)$ of a right-continuous process stays constant for a while. So there are 3 possibilities:

- (i) The path makes infinitely many jumps overall but only finitely many in a given interval $[0, t]$.
- (ii) The path makes finitely many jumps & then gets absorbed in some state.
- (iii) The path makes infinitely jumps in a finite time interval. After the ‘explosion time’ ζ , the process starts up again.

Write $J_0 = 0, J_1, J_2, \dots$ for the jump times and S_1, S_2, \dots for the holding times, defined by

$$J_0 = 0, \quad J_{n+1} = \inf\{t \geq J_n : X_t \neq X_{J_n}\},$$

$$S_n = \begin{cases} J_n - J_{n-1} & J_{n-1} < \infty \\ \infty & \text{otherwise} \end{cases}.$$

By right-continuity, $S_n > 0$ for all n . If $J_{n+1} = \infty$ for some n , we define $X_\infty = X_{J_n}$ as the final value, otherwise X_∞ is not defined. The explosion time ζ is defined by

$$\zeta = \sup(J_n) = \sum_{n=1}^{\infty} S_n.$$

We are not going to consider what happens to a chain after explosion. We thus set $X_t = \infty$ for all $t \geq \zeta$ (adjoining a new state ‘ ∞ ’). We call such a chain *minimal*.

Definition. We define the *jump chain* Y_n of $(X_t)_{t \geq 0}$ by setting $Y_n = X_{J_n}$ for all n .

Definition. A right-continuous random process $X = (X_t)_{t \geq 0}$ has the Markov property (and is called a continuous-time Markov chain) if for all $i_1, i_2, \dots, i_n \in I$ and $0 \leq t_1 < t_2 < \dots < t_n$,

$$\mathbb{P}(X_{t_n} = i_n | X_{t_{n-1}} = i_{n-1}, \dots, X_{t_0} = i_0) = \mathbb{P}(X_{t_n} = i_n | X_{t_0} = i_0).$$

Remark. For all $h > 0$, $Y_n = X(hn)$ defines a discrete-time Markov Chain.

Definition. The transition probabilities are $P_{ij}(s, t) = \mathbb{P}(X_t = j | X_s = i)$, $s \leq t$, $i, j \in I$. It is called *time-homogeneous* if it depends on $t - s$ only, i.e

$$P_{ij}(s, t) = P_{i,j}(0, t - s).$$

In this case we just write $P_{ij}(t - s)$. As in the case of discrete time, a (time-homogeneous) Markov process is characterised by

1. Its initial distribution $\lambda_i = \mathbb{P}(X_0 = i)$, $i \in I$;
2. Its *family of transition matrices* $(P(t))_{t \geq 0} = (P_{ij}(t))_{t \geq 0}$.

The family $(P(t))_{t \geq 0}$ is called the *transition subgroup* of the MC.

A (time-homogeneous) Markov process is characterised by

- its initial distribution;
- its transition subgroup $(P(t))_{t \geq 0}$

$$(P(t))_{t \geq 0} = (P(t))_{\substack{i, j \in I \\ t \geq 0}} = (\mathbb{P}(X_t = j | X_0 = i))_{\substack{i, j \in I \\ t \geq 0}}$$

It is easy to see that

- $P(0)$ is the identity
- $P(t)$ is a stochastic matrix for all t (i.e rows sum to 1)
- $P(t+s) = P(t)P(s) \forall s, t$ (Chapman-Kolmogorov equation)

$$\begin{aligned} P_{xz}(t+s) &= \mathbb{P}(X_{t+s} = z | X_0 = x) \\ &= \sum_{y \in I} \mathbb{P}(X_{t+s} = z | X_0 = x, X_t = y) \mathbb{P}(X_t = y | X_0 = x) \\ &= \sum_{y \in I} \mathbb{P}(X_s = z | X_0 = y) \mathbb{P}(X_t = y | X_0 = x) \\ &= \sum_{y \in I} P_{yz}(s) P_{xy}(t) = P_{x \cdot}(t) P_{\cdot z}(s) \end{aligned}$$

Holding times

Let X be a (right-continuous continuous-time time-homogeneous) Markov Chain on a countable state-space I .

Suppose X starts from $x \in I$. Question: how long does X stay in the state x ?

Definition. We call S_x the *holding time* at state x ($S_x > 0$ by right-continuity).

Let $s, t \geq 0$. Then

$$\begin{aligned} \mathbb{P}(S_x > t+s | S_x > s) &= \mathbb{P}(X_u = x \forall u \in [0, t+s] | X_u = x \forall u \in [0, s]) \\ &= \mathbb{P}(X_u = x \forall u \in [s, t+s] | X_u = x \forall u \in [0, s]) \\ &= \mathbb{P}(X_u = x \forall u \in [s, t+s] | X_s = x) \\ &= \mathbb{P}(X_u = x \forall u \in [0, t] | X_0 = x) \\ &= \mathbb{P}(S_x > t). \end{aligned}$$

Thus S_x has the memoryless property.

By the next theorem, we will get that S_x has the exponential distribution, say with parameter q_x .

Theorem 1.1 (Memoryless property). *Let S be a positive random variable. Then S has the memoryless property, i.e. $\mathbb{P}(S > t + s | S > s) = \mathbb{P}(S > t)$ for all $s, t \geq 0$ if and only if S has the exponential distribution.*

Proof. It is easy to see the exponential distribution is memoryless. So we prove the other direction. Set $F(t) = \mathbb{P}(S > t)$. Then $F(s + t) = F(s)F(t)$ for all $s, t \geq 0$.

Since S is a positive random variable, there exists $n \in \mathbb{N}$ large such that $F(1/n) = \mathbb{P}(S > 1/n) > 0$. Then $F(1) = F(1/n)^n > 0$. So we can set $F(1) = e^{-\lambda}$ for some $\lambda \geq 0$.

For $k \in \mathbb{N}$, $F(k) = F(1)^k = e^{-\lambda k}$. For p/q rational, $F(p/q) = F(1/q)^p = (F(1/q)^q)^{p/q} = F(1)^{p/q} = e^{-\lambda \frac{p}{q}}$.

For any $t \geq 0$, for any $r, s \in \mathbb{Q}$ such that $r \leq t \leq s$, since F is decreasing

$$e^{-\lambda s} = F(s) \leq F(t) \leq F(r) = e^{-\lambda r}.$$

So taking sequences of rationals approaching t , we have $F(t) = e^{-\lambda t}$. \square

Poisson Process'

We are now going to look at the simplest (and most important) example of continuous time Markov Chains - the Poisson process.

Definition. Suppose S_1, S_2, \dots are iid random variables with $S_1 \sim \text{Exp}(\lambda)$. Define the *jump times* $J_0 = 0, J_1 = S_1, J_n = S_1 + \dots + S_n$ for all n , and set $X_t = i$ if $J_i \leq t < J_{i+1}$. Then $I = \{0, 1, 2, \dots\}$ and note that X is right-continuous and increasing. X is called a *Poisson process* of parameter/intensity λ . We sometimes refer to the jump times $(J_i)_{i \geq 1}$ as the *points* of the Poisson process, then X = number of points in $[0, t]$.

Theorem 1.2 (Markov property). *Let $(X_t)_{t \geq 0}$ be a Poisson process of intensity λ . Then for all $s \geq 0$, the process $(X_{s+t} - X_s)_{t \geq 0}$ is also a Poisson process of intensity λ , and is independent of $(X_t)_{0 \leq t \leq s}$.*

Proof. Set $Y_t = X_{t+s} - X_s$ for all $t \geq 0$. Let $i \in \{0, 1, 2, \dots\}$ and condition on $\{X_s = i\}$. Then the jump times for the process Y are $J_{n+1} - s, J_{n+2} - s, \dots$ and the holding times are

$$\begin{aligned} T_1 &= J_{n+1} - s = S_{i+1} - (s - J_i) \\ T_2 &= S_{i+2} \\ T_3 &= S_{i+3} \\ &\vdots \end{aligned}$$

Since $\{X_s = i\} = \{J_i \leq s\} \cap \{s < J_{i+1}\} = \{J_i \leq s\} \cap \{S_{i+1} > s - J_i\}$, conditional on $\{X_s = i\}$, by the memoryless property of the exponential distribution (and

independence of S_{i+1} and J_i) we see that $T_1 \sim \text{Exp}(\lambda)$. Moreover the times J_j , $j \geq 2$ are independent of S_k , $k \leq i$ and hence independent of $(X_r)_{r \leq s}$, and they have iid $\text{Exp}(\lambda)$ distribution. Thus $((X_{s+t} - X_s))_{t \geq 0}$ is a Poisson process of parameter λ and is independent of $(X_t)_{0 \leq t \leq s}$. \square

Similar to this, one can show the Strong Markov property for a Poisson process of parameter λ . Recall a random variable $T \in [0, \infty]$ is called a *stopping time* if for all t , the event $\{T \leq t\}$ depends only on $(X_s)_{s \leq t}$.

Theorem 1.3 (Strong Markov property). *Let $(X_t)_{t \geq 0}$ be a Poisson process of parameter λ and T a stopping time. Then conditional on $T < \infty$, the process $(X_{T+t} - X_T)_{t \geq 0}$ is a Poisson process of parameter λ and independent of $(X_s)_{s \leq T}$.*

Theorem 1.4. Let $(X_t)_{t \geq 0}$ be an increasing right-continuous process taking values in $\{0, 1, 2, \dots\}$ with $X_0 = 0$. Let $\lambda > 0$. Then the following are equivalent

- (a) The holding times S_1, S_2, \dots are iid $\text{Exp}(\lambda)$ and the jump chain is given by $Y_n = n$ (i.e X is a poisson process of intensity λ)
- (b) (Infinitesimal def) X has independent increments and as $h \downarrow 0$ uniformly in t we have

$$\mathbb{P}(X_{t+h} - X_t = 1) = \lambda h + o(h),$$

$$\mathbb{P}(X_{t+h} - X_t = 0) = 1 - \lambda h + o(h).$$

- (c) X has independent and stationary increments and for all $t \geq 0$, $X_t \sim \text{Poi}(\lambda t)$.

Proof. First we show (a) \Rightarrow (b). If (a) holds, then by the Markov property, the increments are independent and stationary $((X_{t+s} - X_s)_{t \geq 0} \stackrel{d}{=} (X_t - X_0)_{t \geq 0})$. Using stationarity we have (uniformly in t) as $h \rightarrow 0$,

$$\mathbb{P}(X_{t+h} - X_t = 0) = \mathbb{P}(X_h = 0) = \mathbb{P}(S_1 > h) = e^{-\lambda h} = 1 - \lambda h + o(h),$$

$$\mathbb{P}(X_{t+h} - X_t \geq 1) = \mathbb{P}(X_h \geq 1) = \mathbb{P}(S_1 \leq h) = 1 - e^{-\lambda h} = \lambda h + o(h),$$

$$\begin{aligned} \mathbb{P}(X_{t+h} - X_t \geq 2) &= \mathbb{P}(X_h \geq 2) = \mathbb{P}(S_1 + S_2 \leq h) \\ &\leq \mathbb{P}(S_1 \leq h, S_2 \leq h) \\ &= \mathbb{P}(S_1 \leq h)^2 \\ &= (\lambda h + o(h))^2 = o(h). \end{aligned}$$

Now we show (b) \Rightarrow (c). If X satisfies (b), then $(X_{t+s} - X_s)_{t \geq 0}$ also satisfies (b). So X has independent and stationary increments. Now set $p_j(t) = \mathbb{P}(X_t = j)$. Then since increments are independent and X is increasing,

$$\begin{aligned} p_j(t+h) &= \mathbb{P}(X_{t+h} = j) = \sum_{i=0}^j \mathbb{P}(X_t = j-i) \mathbb{P}(X_{t+h} - X_t = i) \\ &= p_j(t)(1 - \lambda h + o(h)) + p_{j-1}(t)(\lambda h + o(h)) + o(h). \end{aligned}$$

Thus, $\frac{p_j(t+h) - p_j(t)}{h} = -\lambda p_j(t) + \lambda p_{j-1}(t) + o(1)$. Setting $s = t + h$, we get

$$\frac{p_j(s) - p_j(s-h)}{h} = -\lambda p_j(s-h) + \lambda p_{j-1}(s-h) + o(1).$$

In particular, $p_j(t)$ is continuous and differentiable with

$$p'_j(t) = -\lambda p_j(t) + \lambda p_{j-1}(t).$$

Differentiating

$$(e^{\lambda t} p(t))' = \lambda e^{\lambda t} p_j(t) + e^{\lambda t} p'_j(t) = \lambda e^{\lambda t} p_{j-1}(t).$$

For $j = 0$ we have $p_0(t + h) = p_0(t)(1 - \lambda h + o(h))$, i.e. $p'_0(t) = -\lambda p_0(t)$ so $p_0(t) = e^{-\lambda t}$. Thus

$$p'_1(t) = -\lambda p_1(t) + \lambda e^{-\lambda t}, \text{ i.e. } p_1(t) = \lambda t e^{-\lambda t}.$$

And by induction

$$p_k(t) = e^{-\lambda t} \frac{(\lambda t)^k}{k!},$$

i.e. $X_t \sim \text{Poi}(\lambda t)$.

Finally we show (c) \Rightarrow (a). We know X has independent stationary increments, We have for $t_1 \leq \dots \leq t_k$, $n_1 \leq \dots \leq n_k$,

$$\begin{aligned} & \mathbb{P}(X_{t_1} = n_1, \dots, X_{t_k} = n_k) \\ &= \mathbb{P}(X_{t_1} = n_1) \underbrace{\mathbb{P}(X_{t_2} - X_{t_1} = n_2 - n_1)}_{\sim \text{Poi}(\lambda(t_2 - t_1))} \dots \underbrace{\mathbb{P}(X_{t_k} - X_{t_{k-1}} = n_k - n_{k-1})}_{\sim \text{Poi}(\lambda(t_k - t_{k-1}))}. \end{aligned}$$

So (c) determines the finite-dimensional distributions (f.d.d) of a right-continuous process X , hence (c) determines X . So (c) \Rightarrow (a).

Question: can we show (a) \Rightarrow (c) directly? Indeed note

$$\begin{aligned} \mathbb{P}(X_t = n) &= \mathbb{P}(S_1 + \dots + S_n \leq t < S_1 + \dots + S_{n+1}) \\ &= \mathbb{P}(S_1 + \dots + S_n \leq t) - \mathbb{P}(S_1 + \dots + S_{n+1} \leq t) \\ &= \int_0^t \lambda e^{-\lambda x} \frac{(\lambda x)^{n-1}}{(n-1)!} dx - \int_0^t \lambda e^{-\lambda x} \frac{(\lambda x)^n}{n!} dx \\ &= e^{-\lambda t} \frac{(\lambda t)^n}{n!} \text{ (integration by parts).} \end{aligned}$$

□

Theorem 1.5 (Superposition). *Let X and Y be two independent Poisson processes with parameters λ and μ respectively. Then $(Z_t)_{t \geq 0} = (X_t + Y_t)_{t \geq 0}$ is a Poisson process with parameter $\lambda + \mu$.*

Proof. We use (c) from the previous theorem. So Z has stationary independent increments. Also $Z_t \sim \text{Poi}(\lambda t + \mu t)$. □

Theorem 1.6 (Thinning). *Let X be a Poisson process with parameter λ . Let $(Z_i)_{i \geq 1}$ be a sequence of iid Bernoulli(p) random variables. Let Y be a Poisson process with values in $\{0, \dots\}$ which jumps at time t if and only if X_t jumps at time t and $Z_{X_t} = 1$.*

In other words, we keep every point of X with probability p independently. Then Y is another Poisson process, with parameter λp and $X - Y$ is an independent Poisson process with parameter $\lambda(1 - p)$.

Proof. We shall use the infinitesimal definition. The independence of increments for Y is clear. Since $\mathbb{P}(X_{t+h} - X_t \geq 2) = o(h)$, we have

$$\mathbb{P}(Y_{t+h} - Y_t = 1) = p\mathbb{P}(X_{t+h} - X_t = 1) + o(h) = p\lambda h + o(h),$$

$$\begin{aligned}\mathbb{P}(Y_{t+h} - Y_t = 0) &= \mathbb{P}(X_{t+h} - X_t = 0) + (1-p)\mathbb{P}(X_{t+h} - X_t = 1) + o(h) \\ &= 1 - \lambda h + (1-p)(\lambda h + o(h)) + o(h) \\ &= 1 - \lambda p h + o(h).\end{aligned}$$

Hence Y is Poisson of parameter λp . Clearly $X - Y$ is a thinning of X with Bernoulli parameter $1 - p$, so $X - Y$ is Poisson of parameter $\lambda(1 - p)$.

Now we show Y and $X - Y$ are independent. It is enough to show that the f.d.d of Y and $X - Y$ are independent, i.e if $0 \leq t_1 \leq t_2 \leq \dots \leq t_k$, $n_1 \leq \dots \leq n_k$ and $m_1 \leq \dots \leq m_k$, then we want to prove

$$\begin{aligned}\mathbb{P}(Y_{t_1} = n_1, \dots, Y_{t_k} = n_k, X_{t_1} - Y_{t_1} = m_1, \dots, X_{t_k} - Y_{t_k} = m_k) \\ = \mathbb{P}(X_{t_1} = n_1, \dots, Y_{t_k} = n_k) \mathbb{P}(X_{t_1} - Y_{t_1} = m_1, \dots, X_{t_k} - Y_{t_k} = m_k).\end{aligned}$$

We will only show this for fixed t ($k = 1$) the general case follows similarly using independence of increments. We have

$$\begin{aligned}\mathbb{P}(Y_t = n, X_t - Y_t = m) &= \mathbb{P}(X_t = m + n, Y_t = n) \\ &= \mathbb{P}(X_t = m + n) \mathbb{P}(Y_t = n | X_t = m + n) \\ &= e^{-\lambda t} \frac{(\lambda t)^{m+n}}{(m+n)!} \binom{m+n}{n} p^n (1-p)^m \\ &= e^{-\lambda t p} \frac{(\lambda t p)^n}{n!} e^{-\lambda t(1-p)} \frac{(\lambda t(1-p))^m}{m!} \\ &= \mathbb{P}(X_t = n) \mathbb{P}(X_t - Y_t = m),\end{aligned}$$

as required. □

Theorem 1.7. *Let X be a Poisson Process. Conditional on the event $(X_t = n)$, the jump times J_1, J_2, \dots, J_n are distributed as the order statistics of n iid $U[0, t]$ random variables. That is, they have joint density*

$$f(t_1, \dots, t_n) = \frac{n!}{t^n} \mathbb{1}(0 \leq t_1 \leq \dots \leq t_n \leq t).$$

Proof. Since S_1, S_2, \dots are iid $\text{Exp}(\lambda)$, the joint density of (S_1, \dots, S_{n+1}) is

$$\lambda^{n+1} e^{-\lambda(S_1 + \dots + S_{n+1})} \mathbb{1}(S_i \geq 0 \text{ for all } i).$$

Then the jump times $J_1 = S_1, J_2 = S_1 + S_2, \dots, J_{n+1} = S_1 + \dots + S_{n+1}$ have joint density

$$g(t_1, \dots, t_{n+1}) = \lambda^{n+1} e^{-\lambda t_{n+1}} \mathbb{1}(0 \leq t_1 \leq t_2 \leq \dots \leq t_{n+1}).$$

(Noting the Jacobian of the transformation is 1.) Now take $A \subseteq \mathbb{R}^n$ so

$$\mathbb{P}((J_1, \dots, J_n) \in A | X_t = n) = \frac{\mathbb{P}((J_1, \dots, J_n) \in A | X_t = n)}{\mathbb{P}(X_t = n)}.$$

Note

$$\begin{aligned} & \mathbb{P}((J_1, \dots, J_n) \in A, X_t = n) \\ &= \mathbb{P}((J_1, \dots, J_n) \in A, J_n \leq t < J_{n+1}) \\ &= \int_{(t_1, \dots, t_{n+1}) \in A \times \mathbb{R}} g(t_1, \dots, t_n) \mathbb{1}(t_{n+1} \geq t \geq t_n) dt_1 \dots dt_{n+1} \\ &= \int_A \int_t^\infty \lambda^{n+1} e^{-\lambda t_{n+1}} \mathbb{1}(0 \leq t_1 \leq \dots \leq t_n \leq t) dt_{n+1} dt_1 \dots dt_n \\ &= \int_A \lambda^n e^{-\lambda t} \mathbb{1}(0 \leq t_1 \leq \dots \leq t_n \leq t) dt_1 \dots dt_n. \end{aligned}$$

Then we get

$$\mathbb{P}((J_1, \dots, J_n) \in A | X_t = n) = \int_A \frac{n!}{t^n} \mathbb{1}(0 \leq t_1 \leq \dots \leq t_n \leq t) dt_1 \dots dt_n.$$

As required. \square

Now we look at a generalisation of a Poisson Process: called a Birth Process. For a Poisson Process, the rate of going from i to $i+1$ is λ . For a Birth Process, this is q_i (can depend on i). More precisely:

Definition (Birth Process). For each i , let $S_i = \text{Exp}(q_i)$ with S_1, S_2, \dots independent. Set $J_i = S_1 + \dots + S_i$ and $X_t = i$ if $J_i \leq t < J_{i+1}$. Then X is called a *Birth Process*.

We have some special cases:

1. Simple birth process: when $q_i = \lambda i$ for $i = 1, 2, \dots$;
2. Poisson Process $q_i = \lambda$ for all i .

Motivation for Simple Birth Process (SBP): at time 0 there is only one ‘individual’ i.e $X_0 = 1$. Each individual has an exponential clock of parameter λ independently. Then if there are i individuals, the first clock rings after $\text{Exp}(\lambda i)$ time, and we jump from i to $i + 1$ individuals. Indeed, by the memoryless property, the process begins afresh after each jump.

Proposition 1.8. *Let $(T_k)_{k \geq 1}$ be a sequence of independent random variables with $T_K \sim \text{Exp}(q_k)$ and $\sum_k q_k < \infty$. Let $T = \inf_k T_k$. Then*

- (a) $T \sim \text{Exp}(\sum_k q_k)$
- (b) *The infimum is attained at a point T_K almost surely, and*

$$\mathbb{P}(K = n) = \frac{q_n}{\sum_k q_k}.$$

- (c) T and K are independent.

Proof. See example sheet. □

The main difference between a Poisson Process and a Birth Process is that there is the possibility of explosion in the Birth Process. Recall explosion occurs when $\zeta := \sum_n S_n < \infty$.

Proposition 1.9. *Let X be a Birth Process with rates q_i and $X_0 = 1$. Then*

1. *If $\sum_{i=1}^{\infty} \frac{1}{q_i} < \infty$, then X is explosive, i.e $\mathbb{P}(\zeta < \infty) = 1$;*
2. *If $\sum_{i=1}^{\infty} \frac{1}{q_i} = \infty$, then X is non-explosive, i.e $\mathbb{P}(\zeta = \infty) = 1$.*

Remark. This shows the SBP (as well as the PP) is non-explosive.

Proof.

1. If $\sum_n \frac{1}{q_n} < \infty$, then

$$\mathbb{E}[\zeta] = \mathbb{E} \left[\sum_n S_n \right] = \sum_n \mathbb{E} S_n = \sum_n \frac{1}{q_n} < \infty.$$

Where we have swapped summation and expectation by the MCT (monotone convergence theorem). Thus $\zeta = \sum_n S_n < \infty$ almost surely.

2. If $\sum_n \frac{1}{q_n} = \infty$, then $\prod_n \left(1 + \frac{1}{q_n}\right) \geq 1 + \sum_n \frac{1}{q_n} = \infty$. Then

$$\begin{aligned}
 \mathbb{E}[e^{-\zeta}] &= \mathbb{E}\left[e^{-\sum_{n=1}^{\infty} S_n}\right] \\
 &= \lim_{n \rightarrow \infty} \mathbb{E}\left[e^{-\sum_{i=1}^n S_i}\right] && \text{(MCT)} \\
 &= \lim_{n \rightarrow \infty} \prod_{i=1}^n \mathbb{E}[e^{-S_i}] && \text{(independence)} \\
 &\leq \lim_{n \rightarrow \infty} \prod_{i=1}^n \frac{1}{1 + 1/q_i} = 0.
 \end{aligned}$$

Since $e^{-\zeta} \geq 0$, since $\mathbb{E}(e^{-\zeta}) = 0$ we have $e^{-\zeta} = 0$ almsot surely, i.e $\mathbb{P}(\zeta = \infty) = 1$.

□

Theorem 1.10 (Markov Property). *Let X be a BP with parameters (q_i) . Conditional on $X_s = i$, the process $(X_{s+t})_{t \geq 0}$ is a birth process with rates $(q_j)_{j \geq i}$ starting from i , and independent of $(X_r)_{r \leq s}$.*

Proof. As in the Poisson Process case. \square

Theorem 1.11. *Let X be an increasing right-continuous process with values in $\{1, 2, \dots\} \cup \{\infty\}$. Let $0 \leq q_j < \infty$ for all $j \geq 0$. Then the following are equivalent:*

1. (jump chain/holding time definition) conditional on $X_s = i$, the holding times S_1, S_2, \dots are independent exponentials with rates q_i, q_{i+1}, \dots respectively and the jump chain is given $Y_n = i + n$ for all n .
2. (infinitesimal definition) for all $t, h \geq 0$, conditional on $X_t = i$, the process $(X_{t+h})_{h \geq 0}$ is independent of $(X_s)_{s \leq t}$ and as $h \rightarrow 0$, uniformly in t we have

$$\mathbb{P}(X_{t+h} = i | X_t = i) = 1 - q_i h + o(h),$$

$$\mathbb{P}(X_{t+h} = i + 1 | X_t = i) = q_i h + o(h).$$

3. (transition probability definition) for all $n = 0, 1, 2, \dots$ and all times $0 \leq t_0 \leq t_1 \leq \dots \leq t_{n+1}$, and all states i_0, i_1, \dots, i_{n+1} ,

$$\mathbb{P}(X_{t_{n+1}} = i_{n+1} | X_0 = i_0, \dots, X_{t_n} = i_n) = p_{i_n, i_{n+1}}(t_{n+1} - t_n),$$

where $(p_{ij}(t) : i, j = 0, 1, 2, \dots)$ is the unique solution to the equation (called Kolmogorov's forward equation)

$$p'_{ij}(t) = q_{j-1} p_{i, j-1}(t) - q_j p_{i, j}(t). \quad (*)$$

(as in the Poisson Process, $p_{ij}(t+h) = p_{i, j-1}(t) q_j h + p_{i, j}(t) (1 - q_j h) + o(h)$.)

Existence and uniqueness of a solution in (3) follow since for $i = j$ $p'_{i, i}(t) = -q_i p_{i, i}(t)$ and $p_{i, i}(0) = 1$, so $p_{i, i}(t) = e^{-q_i t}$. Then by induction, if the unique solution for $p_{i, j}(t)$ exists, then plug into (*) to see there exists a unique solution for $p_{i, j+1}(t)$.

Also note that we can write the equation in matrix form:

$$P'(t) = P(t)Q, \text{ where } Q = \begin{pmatrix} -q_1 & q_1 & 0 & \dots \\ 0 & -q_2 & q_2 & \dots \\ \vdots & \ddots & \ddots & \ddots \end{pmatrix}.$$

Q-matrix and construction of Markov Processes

Definition. $Q = (q_{ij})_{i, j \in I}$ is called a Q -matrix if

- (a) $-\infty < q_{ii} \leq 0$ for all $i \in I$;

(b) $0 \leq q_{ij} < \infty$ for all $i, j \in I$ with $i \neq j$;

(c) $\sum_{j \in I} q_{ij} = 0$ for all $i \in I$.

Write $q_i = -q_{ii} = \sum_{j \notin I} q_{ij}$ for all $i \in I$.

Given a Q -matrix Q , we define a jump matrix P as follows. For $x \neq y$ with $q_x \neq 0$, set $p_{xy} = \frac{q_{xy}}{q_x}$ and $p_{xx} = 0$. If $q_x = 0$, set $p_{xy} = \mathbb{1}(x = y)$.

Example.

$$Q = \begin{pmatrix} -1 & 1 & 0 \\ 1 & -2 & 1 \\ 2 & 1 & -3 \end{pmatrix} \implies P = \begin{pmatrix} 0 & 1 & 0 \\ 1/2 & 0 & 1/2 \\ 2/3 & 1/3 & 0 \end{pmatrix}.$$

Definition. Let Q be a Q -matrix and λ a probability measure on the state space I . Then a (minimal) random process X is a *Markov process* with initial distribution λ and infinitesimal generator Q if

- (a) The jump chain $Y_n = X_{J_n}$ is a discrete time Markov chain starting from $Y_0 \sim \lambda$ with transition matrix P .
- (b) Conditional on Y_0, Y_1, \dots, Y_n , the holding times S_1, \dots, S_{n+1} are independent with $S_i \sim \text{Exp}(q_{Y_{i-1}})$ for $i = 1, \dots, n+1$.

We write $X \sim \text{Markov}(\lambda, Q)$.

Example. Birth-Processes are $\text{Markov}(\lambda, Q)$ with $I = \mathbb{N}$ and

$$Q = \begin{pmatrix} -q_1 & q_1 & 0 & \dots \\ 0 & -q_2 & q_2 & \dots \\ \vdots & \ddots & \ddots & \ddots \end{pmatrix} \text{ and } P = \begin{pmatrix} 0 & 1 & 0 & \dots \\ 0 & 0 & 1 & \dots \\ \vdots & \ddots & \ddots & \ddots \end{pmatrix}.$$

And jump chain $Y_n = Y_0 + n$.

We have multiple constructions of a Markov(λ, Q) process:

Construction 1:

- $(Y_n)_{n \geq 1}$ is a discrete-time Markov chain, $Y_0 \sim \lambda$ & transition matrix P .
- $(T_i)_{i \geq 1}$ iid Exp(1) random variables, independent of Y and set $S_n = \frac{T_n}{q_{Y_{n-1}}}$ and $J_n = \sum_{i=1}^n S_i$ (this implies $S_n \sim \text{Exp}(q_{Y_{n-1}})$) and set $X_t = Y_n$ if $J_n \leq t < J_{n+1}$ and $X_t = \infty$ otherwise.

Construction 2:

- Let $(T_n^y)_{n \geq 1, y \in I}$ be iid Exp(1) random variables
- $Y_0 \sim \lambda$ and inductively define Y_n, S_n : if $Y_n = x$ then for $y \neq x$ define $S_{n+1}^y = \frac{T_{n+1}^y}{q_{xy}} \sim \text{Exp}(q_{xy})$ and $S_{n+1} = \inf_{y \neq x} S_{n+1}^y \sim \text{Exp}\left(\sum_{y \neq x} q_{xy}\right)$, and if $S_{n+1} = S_{n+1}^Z$ for some random Z (since the infimum is attained), take $Y_{n+1} = Z$ (if $q_x > 0$). If $q_x = 0$ take $Y_{n+1} = x$.

(Proof of equivalence: see Example Sheet)

Construction 3:

- For $x \neq y$, let $(N_t^{x,y})$ be independent Poisson Processes with rates q_{xy} respectively. Let $Y_0 \sim \lambda$, $J_0 = 0$ and define inductively:

$$J_{n+1} = \inf\{t > J_n : N_t^{Y_n, y} \neq N_{J_n}^{Y_n, y} \text{ for some } y \neq Y_n\},$$

$$Y_{n+1} = \begin{cases} y & \text{if } J_{n+1} < \infty \text{ and } N_{J_{n+1}}^{Y_n, y} \neq N_{J_n}^{Y_n, y} \\ x & \text{if } J_{n+1} = \infty \end{cases}.$$

For a birth process, we characterised when explosion happens. In general, the next theorem gives a sufficient condition:

Theorem 1.12. *Let X be Markov(λ, Q) on I . Then $\mathbb{P}(\zeta = \infty) = 1$ (non-explosive) if any of the following hold:*

- (a) I is finite;
- (b) $\sup_{x \in I} q_x < \infty$;
- (c) $X_0 = x$ and x is recurrent for the jump chain Y .

Proof. Note that (a) \Rightarrow (b) so it is enough to show in the cases we have (b) or (c). If (b) holds, set $q = \sup_{x \in I} q_x < \infty$. Since $S_n = \frac{T_n}{q_{X_{n-1}}}$, $S_n \geq \frac{T_n}{q}$. Hence

$$\zeta = \sum_{n=1}^{\infty} S_n > \frac{1}{q} \sum_{n=1}^{\infty} T_n = \infty \text{ almost surely (SLLN),}$$

i.e $\mathbb{P}(\zeta = \infty) = 1$.

Now suppose (c) holds. Let $(N_i)_{i \in I}$ be the times when the jump chain Y visits x . By the SLLN,

$$\zeta \geq \sum_{i=1}^{\infty} S_{N_i+1} = \sum_{i=1}^{\infty} \frac{T_{N_i+1}}{q_{N_i}} = \frac{1}{q_x} \sum_{i=1}^{\infty} T_{N_i+1} = \infty \text{ almost surely,}$$

i.e $\mathbb{P}(\zeta = \infty) = 1$. □

Example. Suppose $I = \mathbb{Z}$, $q_{i,i+1} = q_{i,i-1} = 2^{|i|}$ for all i . Then $p_{i,i+1} = p_{i,i-1} = 1/2$ and the jump chain is the symmetric simple random walk on \mathbb{Z} , which is recurrent. Hence X is non-explosive.

Example. Suppose $I = \mathbb{Z}$, $q_{i,i+1} = 2^{|i|+1}$, $q_{i,i-1} = 2^{|i|}$ so $q_i = 2^{|i|} + 2^{|i|+1}$. Then the jump chain Y is a simple random walk with $1/3$ probability of moving towards 0 and $2/3$ probability of moving away from 0, hence is transient. We have

$$\mathbb{E}[\zeta] = \mathbb{E} \left[\sum_{n=1}^{\infty} S_n \right] = \sum_{j \in \mathbb{Z}} \mathbb{E} \left[\sum_{k=1}^{V_j} S_{N_k^j+1} \right],$$

where V_j is the total number of visits to j and N_k^j is the time of the k th visit to j . Hence

$$\sum_{j \in \mathbb{Z}} \mathbb{E} \left[\sum_{k=1}^{V_j} S_{N_k^j+1} \right] = \sum_{j \in \mathbb{Z}} \mathbb{E}[V_j] \mathbb{E}[S_{N_1^j+1}] = \sum_{j \in \mathbb{Z}} \mathbb{E}[V_j] \frac{1}{q_j} = \sum_{j \in \mathbb{Z}} \frac{1}{3 \cdot 2^{|j|}} \mathbb{E}V_j.$$

Since $\mathbb{E}V_j \leq 1 + \mathbb{E}_j V_j = 1 + \mathbb{E}_0 V_0 := C < \infty$ (transience) we have

$$\sum_{j \in \mathbb{Z}} \frac{1}{3 \cdot 2^{|j|}} \mathbb{E}V_j \leq \sum_{j \in \mathbb{Z}} \frac{C}{2 \cdot 2^{|j|}} < \infty.$$

So $\mathbb{E}[\zeta] < \infty$ and $\mathbb{P}(\zeta < \infty) = 1$, i.e explosive.

Theorem 1.13 (Strong Markov Property). *Let X be Markov(λ, Q) and let T be a stopping time. Then conditional on $T < \zeta$ and $X_T = x$, the process $(X_{T+t})_{t \geq 0}$ is Markov(δ_x, Q) and independent of $(X_s)_{s \leq T}$.*

Proof. Omitted (uses measure theory, see Norris (6.5)). □

Kolmogorov's forward & backward equations

We work on a countable state space I .

Theorem 1.14. *Let X be a minimal right-continuous process with values in a countable set I . Let Q be a Q -matrix with jump matrix P . Then the following are equivalent:*

(a) X is a continuous-time Markov chain with generator Q .

(b) For all $n \geq 0$, $0 \leq t_0 \leq \dots \leq t_{n+1}$, and all states $x_0, \dots, x_{n+1} \in I$,

$$\mathbb{P}(X_{t_{n+1}} = x_{n+1} | X_{t_n} = x_n, \dots, X_{t_0} = x_0) = p_{x_n x_{n+1}}(t_{n+1} - t_n).$$

Where $(P(t)) = (p_{xy}(t))$ is the minimal non-negative solution to the backward equation

$$P'(t) = QP(t), \text{ with } P(0) = I.$$

(Minimality means that if \tilde{P} is another non-negative solution, we have $p_{xy}(t) \leq \tilde{p}_{xy}(t)$ for all t and all $x, y \in I$.) In fact, if the chain is non-explosive, the solution is unique.

(c) $P(t)$ is the minimal non-negative solution to the forward equation

$$P'(t) = P(t)Q, \text{ with } P(0) = I.$$

Note. We shall skip the proof of the equivalence of (c) (see Norris (2.8)).

Proof. First we show (a) \Rightarrow (b). If $(J_n)_{n \geq 1}$ denote the jump times, then

$$\mathbb{P}_x(X_t = y, J_1 > t) = \mathbb{1}(x = y)e^{-q_x t}.$$

Integrating over the values of $J_1 \leq t$ and using independence of the jump chain, for $z \neq x$,

$$\begin{aligned} \mathbb{P}_x(X_t = y, J_1 \leq t, X_{J_1} = z) &= \int_0^t q_x e^{-q_x s} \frac{q_{xz}}{q_x} p_{zy}(t-s) ds \\ &= \int_0^t e^{-q_x s} q_{xz} p_{zy}(t-s) ds \end{aligned}$$

Summing over all $z \neq x$ (and by the MCT),

$$\mathbb{P}_x(X_t = y, J_1 \leq t) = \int_0^t \sum_{z \neq x} e^{-q_x s} q_{xz} p_{zy}(t-s) ds.$$

So

$$p_{xy}(t) = \mathbb{P}_x(X_t = y) = e^{-q_x t} \mathbb{1}(x = y) + \int_0^t \sum_{z \neq x} e^{-q_x s} q_{xz} p_{zy}(t-s) ds.$$

And by a substitution

$$e^{q_x t} p_{xy}(t) = \mathbb{1}(x = y) + \int_0^t \sum_{z \neq x} e^{q_x u} q_{xz} p_{zy}(u) du.$$

Hence $p_{xy}(t)$ is a continuous function in t , and hence

$$\sum_{z \neq x} e^{q_x u} q_{xz} p_{zy}(u)$$

is a series of continuous functions, and is also uniformly convergence (Weierstrass-M test), so continuous. Hence $e^{q_x t} p_{xy}(t)$ is differentiable with derivative

$$e^{q_x t} (q_x p_{xy}(t) + p'_{xy}(t)) = \sum_{z \neq x} e^{q_x t} q_{xz} p_{zy}(t).$$

Thus

$$p'_{xy}(t) = \sum_z q_{xz} p_{zy}(t) \implies P'(t) = QP(t).$$

Now we show minimality: let \tilde{P} be another non-negative solution of the backward equation. We will show $p_{xy}(t) \leq \tilde{p}_{xy}(t)$ for all x, y, t . As before,

$$\begin{aligned} \mathbb{P}_x(X_t = y, t < J_{n+1}) &= \mathbb{P}_x(X_t = y, J_1 > t) + \mathbb{P}_x(X_t = y, J_1 \leq t < J_{n+1}) \\ &= e^{-q_x t} \mathbb{1}(x = y) + \sum_{z \neq x} \int_0^t q_x e^{-q_x s} \frac{q_{xz}}{q_x} \mathbb{P}_z(X_{t-s} = y, t-s < J_n) ds. \end{aligned}$$

Now, as \tilde{P} satisfies the backward equation, we get as before (retracing previous steps)

$$\tilde{p}_{xy}(t) = e^{-q_x t} \mathbb{1}(x = y) + \sum_{z \neq x} \int_0^t e^{-q_x s} q_{xz} \tilde{p}_{zy}(t-s) ds. \quad (*)$$

Now we prove by induction that

$$\mathbb{P}_x(X_t = y, t < J_n) \leq \tilde{p}_{xy}(t) \text{ for all } n.$$

For $n = 1$,

$$e^{-q_x t} \mathbb{1}(x = y) \leq \tilde{p}_{xy}(t) \text{ by } (*).$$

Assume true for some $n \in \mathbb{N}$. Then for $n + 1$,

$$\mathbb{P}_x(X_t = y, t < J_{n+1}) \leq e^{-q_x t} \mathbb{1}(x = y) + \sum_{z \neq x} \int_0^t q_{xz} e^{-q_x s} \tilde{p}_{zy}(t-s) ds = \tilde{p}_{xy}(t).$$

So it holds for all n . Hence

$$\lim_{n \rightarrow \infty} \mathbb{P}_x(X_t = y, t < J_n) = \mathbb{P}_x(X_t = y, t < \zeta) \leq \tilde{p}_{xy}.$$

(Since $J_n \uparrow \zeta$.) Now by minimality,

$$p_{xy}(t) = \mathbb{P}_x(X_t = y) = \mathbb{P}_x(X_t = y, t < \zeta) \leq \tilde{p}_{xy}(t).$$

□

Finite state space:

Definition. If A is a finite-dimensional square matrix, its matrix exponential is given by

$$e^A = \sum_{k=0}^{\infty} \frac{A^k}{k!} = I + A + \frac{A^2}{2!} + \dots$$

Claim. For any $r \times r$ matrix A , the exponential e^A is an $r \times r$ matrix. If A_1 and A_2 commute, then $e^{A_1+A_2} = e^{A_1} e^{A_2}$.

Proof. Example Sheet. □

Proposition 1.15. Let Q be a Q -matrix on a finite set I and $P(t) = e^{tQ}$. Then

- (i) $P(t+s) = P(t)P(s)$ for all s, t ;
- (ii) $(P(t))_{t \geq 0}$ is the unique solution to the forward equation $P'(t) = P(t)Q$, $P(0) = I$;
- (iii) $(P(t))_{t \geq 0}$ is the unique solution to the backward equation $P'(t) = QP(t)$, $P(0) = I$;
- (iv) For $k = 0, 1, 2, \dots$, $\left(\frac{d}{dt}\right)^k P(t) \Big|_{t=0} = Q^k$.

Proof.

- (i) Since tQ and sQ commute, $\exp((t+s)Q) = \exp(tQ)\exp(sQ)$.
- (ii) The sum in e^{tQ} has infinite radius of convergence, hence we can differentiate term by term.
- (iii) Same as (ii).
- (iv) Same again.

Now we'll show uniqueness in (ii) and (iii). If \tilde{P} is another solution to the forward equation, $\tilde{P}'(t) = \tilde{P}(t)Q$, $\tilde{P}(0) = I$, then

$$\begin{aligned}\frac{d}{dt} \left(\tilde{P}(t)e^{-tQ} \right) &= \tilde{P}'(t)e^{-tQ} + \tilde{P}(t) (-Qe^{-tQ}) \\ &= \tilde{P}(t)Qe^{-tQ} - \tilde{P}(t)Qe^{-tQ} = 0\end{aligned}$$

So $\tilde{P}(t)e^{-tQ}$ is a constant matrix. Since $\tilde{P}(0) = I$, this implies $\tilde{P}(t) = e^{tQ}$. The same thing works for the backward equation. \square

Example. Let $Q = \begin{pmatrix} -2 & 1 & 1 \\ 1 & -1 & 0 \\ 2 & 1 & -3 \end{pmatrix}$. To find $p_{11}(t)$, we can diagonalise $Q = PDP^{-1}$ for a diagonal matrix

$$D = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

so

$$e^{tQ} = Pe^{tD}P^{-1} = P \begin{pmatrix} e^{t\lambda_1} & 0 & 0 \\ 0 & e^{t\lambda_2} & 0 \\ 0 & 0 & e^{t\lambda_3} \end{pmatrix} P^{-1}.$$

i.e $p_{11}(t) = ae^{t\lambda_1} + be^{t\lambda_2} + ce^{t\lambda_3}$, which we can solve by considering $p_{11}(0), p'_{11}(0), p''_{11}(0)$.

Theorem 1.16. *Let I be a finite state space and Q be a matrix. Then it is a Q -matrix iff $P(t) = e^{tQ}$ is a stochastic matrix for all t .*

Proof. For t sufficiently small, $p(t) = e^{tQ} = I + tQ + \mathcal{O}(t^2)$, so for all $x \neq y$, $q_{xy} \geq 0$ iff $p_{xy}(t) \geq 0$ for all t sufficiently small.

Since $P(t) = (P(t/n))^n$ for all n , we get $q_{xy} \geq 0$ for all $x \neq y$ iff $p_{xy}(t) \geq 0$ for all $t \geq 0$.

Assume now that Q is a Q -matrix, i.e. $\sum_y q_{xy} = 0$ for all x . Then $\sum_y (Q^n)_{xy} = \sum_y \sum_z (Q^{n-1})_{xz} Q_{zy} = \sum_z Q_{xz}^{n-1} \sum_y Q_{zy} = 0$. Hence $Q^n \mathbf{1} = Q^{n-1} Q \mathbf{1} = 0$ ($\mathbf{1}$ is vector with all entries 1). Hence, since

$$p_{xy}(t) = \delta_{xy} + \sum_{k=1}^{\infty} \frac{t^k}{k!} (Q^k)_{xy}$$

we have $\sum_y p_{xy}(t) = 1 + \sum_{k=1}^{\infty} \frac{t^k}{k!} \sum_y (Q^k)_{xy} = 1$. i.e $P(t)$ is a stochastic matrix.

Assume now that $P(t)$ is a stochastic matrix. Then as $Q = \left. \frac{d}{dt} P(t) \right|_{t=0}$, we have

$$\sum_y q_{xy} = \left. \frac{d}{dt} \sum_y p_{xy}(t) \right|_{t=0} = 0.$$

i.e Q is a Q -matrix. □

Theorem 1.17. *Let X be a right-continuous process with values in a finite set I , and let Q be a Q -matrix on I . Then the following are equivalent*

- (a) *The process X is Markov with generator Q (Markov(Q));*
- (b) *(infinitesimal definition) Conditional on $X_s = x$, the process $(X_{s+t})_{t \geq 0}$ is independent of $(X_r)_{r \leq s}$ and uniformly in t as $h \downarrow 0$, for all x, y*

$$\mathbb{P}(X_{t+h} = y | X_t = x) = \mathbb{1}(x = y) + q_{xy}h + o(h)$$

- (c) *For all $n \geq 0$, $0 \leq t_0 \leq \dots \leq t_n$ and all states x_0, \dots, x_n ,*

$$\mathbb{P}(X_{t_n} = x_n | X_{t_0} = x_0, \dots, X_{t_{n-1}} = x_{n-1}) = p_{x_{n-1}, x_n}(t_n - t_{n-1})$$

where $(p_{xy}(t))$ is the solution to the forward equation $P'(t) = P(t)Q$, $P(0) = I$.

Proof. We have already shown (a) \iff (b) (from countable setting), so it is enough to show (b) \iff (c).

First we show (c) \implies (b). $P(t) = e^{tQ}$ is the solution (as I is finite). As $t \downarrow 0$, $P(t) = I + tQ + \mathcal{O}(t^2)$. Thus for all $t > 0$ and as $h \downarrow 0$, $\forall x, y$,

$$\mathbb{P}(X_{t+h} = y | X_t = x) = \mathbb{P}(X_h = y | X_0 = x) = p_{xy}(h) = \delta_{xy} + hq_{xy} + o(h).$$

Now we show (b) \Rightarrow (c). We have

$$p_{xy}(t+h) = \sum_z p_{xz}(t)(\mathbb{1}(z=y) + q_{zy}h + o(h)).$$

So

$$\frac{p_{xy}(t+h) - p_{xy}(t)}{h} = \sum_z p_{xz}(t)q_{zy} + o(1).$$

As $h \downarrow 0$,

$$p'_{xy}(t) = \sum_z p_{xz}(t)q_{zy} = (P(t)Q)_{xy}.$$

□

Remark. To get the backward equation we could write

$$p_{xy}(t+h) = \sum_z p_{xz}(h)p_{zy}(t)$$

and continue similarly.

2 Qualitative Properties of Continuous Time Markov Chains

We have minimal chains, and countable state space.

Class Structure

Definition. For states $x, y \in I$, write $x \rightarrow y$ (“ x leads to y ”) if $\mathbb{P}_x(X_t = y \text{ for some } t \geq 0) > 0$. We write $x \leftrightarrow y$ (“ x communicates with y ”) if $x \rightarrow y$ and $y \rightarrow x$. Clearly this is an equivalence relation and we call the equivalence classes *communicating classes*. We define *irreducibility*, *closed class* and *absorbing states* exactly as in discrete Markov Chains.

Proposition 2.1. Let X be Markov(Q) with transition semigroup $(P(t))_{t \geq 0}$. For any 2 states $x, y \in I$, the following are equivalent

- (a) $x \rightarrow y$;
- (b) $x \rightarrow y$ for the jump chain;
- (c) $q_{x_0 x_1} \cdots q_{x_{n-1} x_n} > 0$ for some $x = x_0, x_1, \dots, x_{n-1}, x_n = y$;
- (d) $p_{xy}(t) > 0$ for all $t > 0$;
- (e) $p_{xy}(t) > 0$ for some $t > 0$.

Proof. Clearly (d) \Rightarrow (e) \Rightarrow (a) \Rightarrow (b). Now we show (b) \Rightarrow (c). Since $x \rightarrow y$ for the jump chain, there exist $x_0 = x, x_1, \dots, x_{n-1}, x_n = y \in I$ such that

$$p_{x_0 x_1} p_{x_1 x_2} \dots p_{x_{n-1} x_n} > 0.$$

Hence $q_{x_0 x_1} q_{x_1 x_2} \dots q_{x_{n-1} x_n}$ since $q_{xy}/q_x = p_{xy}$.

Now we show (c) \Rightarrow (d). For any 2 states w, z with $q_{wz} > 0$, and for any $t > 0$,

$$p_{wz}(t) \geq \mathbb{P}_w(J_1 \leq t, Y_1 = z, S_2 > t) = (1 - e^{-q_w t}) \frac{q_{wz}}{q_w} e^{-q_z t} > 0.$$

i.e $q_{wz} > 0$ implies $q_{wz}(t) > 0$ for all t . Hence if (c) holds, $p_{x_i x_{i+1}}(t) > 0$ for all t and all $0 \leq i \leq n-1$. Then $p_{xy}(t) = p_{x_0 x_1}(t/n) p_{x_1 x_2}(t/n) \dots p_{x_{n-1} x_n}(t/n) > 0$. \square

Hitting times

Definition. Let Y be the jump chain associated with X , and $A \subseteq I$. Set $T_A = \inf\{t > 0 : X_t \in A\}$, $H_A = \inf\{n \geq 0 : Y_n \in A\}$, $h_A(x) = \mathbb{P}_x(T_A < \infty)$ (hitting probability), $k_A(x) = \mathbb{E}_x T_A$ (mean hitting time).

Note. The hitting probability for X is the same as that for Y but the mean hitting times will differ in general.

Theorem 2.2. $(h_A(x))_{x \in I}$ and $(k_A(x))_{x \in I}$ are the minimal non-negative solutions to

$$\begin{cases} h_A(x) = 1 & \forall x \in A \\ Qh_A(x) = \sum_y q_{xy} h_A(y) = 0 & \forall x \notin A \end{cases}$$

and

$$\begin{cases} k_A(x) = 0 & \forall x \in A \\ Qk_A(x) = \sum_y q_{xy} k_A(y) = -1 & \forall x \notin A \end{cases}$$

respectively (assume $q_x > 0$ for all $x \notin A$).

Proof. The hitting probabilities are the same as those for the jump chain. Hence $h_A(x) = 1$ for all $x \in A$ and $h_A(x) = \sum_{y \neq x} p_{xy} h_A(y)$ for all $x \notin A$. Hence for all $x \notin A$

$$q_x h_A(x) = \sum_{y \neq x} h_A(y) q_{xy} \implies \sum_y h_A(y) q_{xy} = 0.$$

Clearly if $x \in A$, $T_A = 0$, so $k_A(x) = 0$. Let $x \notin A$. Then $J_1 \leq T_A$, and hence

$$\begin{aligned} k_A(x) &= \mathbb{E}_x T_A \\ &= \mathbb{E}_x J_1 + \mathbb{E}_x (T_A - J_1) \\ &= \mathbb{E}_x J_1 + \sum_{y \neq x} \mathbb{E}_x (T_A - J_1 | Y_1 = y) p_{xy} \\ &= \frac{1}{q_x} + \sum_{y \neq x} k_A(y) \frac{q_{xy}}{q_x}. \end{aligned}$$

Therefore

$$q_x k_A(x) = 1 + \sum_{y \neq x} q_{xy} k_A(y) \implies \sum_y q_{xy} k_A(y) = -1.$$

The minimality of solutions is as in the discrete chain. □

Recurrence and Transience

Definition. The state x is called *recurrent* for X if

$$\mathbb{P}(\{t : X_t = x\} \text{ is unbounded}) = 1.$$

The state x is called *transient* if

$$\mathbb{P}(\{t : X_t = x\} \text{ is unbounded}) = 0.$$

Remark. If X explodes with positive probability starting from x , i.e. $\mathbb{P}(\zeta < \infty) > 0$, then $\sup_t \{t : X_t = x\} \leq \zeta < \infty$ with positive probability so x cannot be recurrent.

Theorem 2.3. Let X be Markov(Q) with jump chain Y . Then

- (a) If x is recurrent for Y , then x is recurrent for X ;
- (b) If x is transient for Y , then x is transient for X ;
- (c) Every state is either recurrent or transient;
- (d) Recurrence and transience are class properties.

Proof. (a) & (b) will imply (c) & (d) through the results for the discrete chain. So we prove (a) and (b).

First we prove (a). Suppose x is recurrent for Y and $X_0 = x$. Then X is not explosive, i.e. $\mathbb{P}(\zeta = \infty) = 1$, so $J_n \rightarrow \infty$ with probability 1 (starting from x). Since $X_{J_n} = Y_n$ for all n , and Y visits x infinitely often with probability 1, $\{t : X_t = x\}$ is unbounded with probability 1.

Now we prove (b). If x is transient for Y , $q_x > 0$ (otherwise x is an absorbing state). Also, almost surely there is a last visit to x for Y , i.e.

$$N := \sup\{n : Y_n = x\} < \infty \text{ almost surely.}$$

Also, $J_{N+1} < \infty$ almost surely (as $q_x > 0$) and if $t \in \{s : X_s = x\}$, then $t \leq J_{N+1}$, i.e. $\sup\{s : X_s = x\} \leq J_{N+1} < \infty$ almost surely. \square

Like in the discrete-time chain, $\sum_{n \geq 1} p_{xx}(n) = \infty$ implies x is recurrent; and $\sum_{n \geq 1} p_{xx}(n) < \infty$ implies x is transient.

Theorem 2.4. x is recurrent for X if and only if $\int_0^\infty p_{xx}(t)dt = \infty$, and x is transient for X if and only if $\int_0^\infty p_{xx}(t)dt < \infty$.

Proof. If $q_{xx} = 0$, then x is absorbing, i.e. $p_{xx}(t) = 1$ for all t and $\int_0^\infty p_{xx}(t)dt = \infty$. Assume $q_x > 0$. Then

$$\begin{aligned}
 \int_0^\infty p_{xx}(t)dt &= \int_0^\infty \mathbb{E}[\mathbb{1}(X_t = x)]dt \\
 &= \mathbb{E}_x \left[\int_0^\infty \mathbb{1}(X_t = x)dt \right] && \text{(Fubini)} \\
 &= \mathbb{E}_x \left[\sum_{n=0}^\infty \mathbb{1}(Y_n = x) S_{n+1} \right] \\
 &= \sum_{n=0}^\infty \mathbb{E}_x [\mathbb{1}(Y_n = x) S_{n+1}] && \text{(Fubini)} \\
 &= \sum_{n=0}^\infty \mathbb{P}_x(Y_n = x) \mathbb{E}_x[S_{n+1} | Y_n = x] \\
 &= \sum_{n=0}^\infty p_{xx}(n) \frac{1}{q_x}.
 \end{aligned}$$

\square

Invariant Distributions

Definition. For a discrete Markov Chain Y , π is an *invariant measure* for Y if $\pi P = \pi$. If in addition $\sum \pi_i = 1$, π is called a *invariant distribution*. Then if $Y_0 \sim \pi$, $Y_n \sim \pi$ for all $n \geq 1$.

Recall:

Theorem 2.5. If Y is a discrete time Markov Chain which is irreducible, recurrent and $x \in I$. Then

$$\nu^x(y) = \mathbb{E}_x \left[\sum_{n=0}^{H_x-1} \mathbb{1}(Y_n = y) \right] \text{ where } H_x = \inf\{n \geq 1 : Y_n = x\}.$$

Then $\nu^x(\cdot)$ is an invariant measure and $0 < \nu^x(y) \leq 1$ for all y , $\nu^x(x) = 1$.

Theorem 2.6. If Y is irreducible, λ is any invariant measure with $\lambda(x) = 1$, then

$$\lambda(y) \geq \nu^x(y) \text{ for all } y.$$

If Y is recurrent then $\lambda(y) = \nu^x(y)$ for all y .

Definition. Let $X \sim \text{Markov}(Q)$ and let λ be a measure. Then λ is called invariant/infinitesimally invariant if $\lambda Q = 0$.

Lemma 2.7. If $|I|$ is finite, then $\lambda Q = 0$ if and only if $\lambda P(s) = \lambda$ for all $s \geq 0$.

Proof. $P(s) = e^{sQ}$ since I is finite. If $\lambda Q = 0$, then

$$\lambda P(s) = \lambda e^{sQ} = \lambda \sum_{k=0}^{\infty} \frac{(sQ)^k}{k!} = I.$$

If $\lambda P(s) = \lambda$ for all s , then

$$\lambda Q = \lambda P'(0) = \left. \frac{d}{ds}(\lambda P(s)) \right|_{s=0} = \left. \frac{d}{ds} \lambda \right|_{s=0} = 0.$$

□

Lemma 2.8. Let X be $\text{Markov}(Q)$ and Y its jump chain. π is invariant for X if and only if μ defined by $\mu_x = q_x \pi_x$ is invariant for Y (i.e. $\pi Q = 0$ if and only if $\mu P = \mu$).

Proof. Since $q_x(p_{xy} - \delta_{xy}) = q_{xy}$,

$$\begin{aligned} (\pi Q)_y &= \sum_{x \in I} \pi_x q_{xy} = \sum_{x \in I} \pi_x q_x (p_{xy} - \delta_{xy}) \\ &= \sum_{x \in I} \mu_x (p_{xy} - \delta_{xy}) \\ &= \sum_x \mu_x p_{xy} - \mu_y \\ &= (\mu P)_y - \mu_y. \end{aligned}$$

□

Theorem 2.9. Let X be irreducible & recurrent, with generator Q . Then X has an invariant measure, which is unique up to scalar multiplication.

Proof. Assume $|I| > 1$. Then by irreducibility, $q_x > 0$ for all x . For Y , $\nu^x(y) = \mathbb{E}_x \left[\sum_{n=0}^{H_x-1} \mathbb{1}(Y_n = y) \right]$ where $H_x = \inf\{n \geq 1 : Y_n = x\}$ is an invariant measure as Y is irreducible & recurrent (since X is), hence ν^x is an invariant measure for Y which is unique up to scalar multiplication. By the previous lemma, $\frac{\nu^x(y)}{q_y}$ is an invariant measure for X , and also unique up to scalar multiplication. □

Definition. Let $T_x = \inf\{t \geq J_1 : X_t = x\}$ be the first return time to x .

Lemma 2.10. Assume $q_y > 0$. Define

$$\mu^x(y) = \mathbb{E}_x \left[\int_0^{T_x} \mathbb{1}(X_t = y) dt \right].$$

Then $\mu^x(y) = \frac{\nu^x(y)}{q_y}$.

Proof.

$$\begin{aligned}
 \mu^x(y) &= \mathbb{E}_x \left[\int_0^{T_x} \mathbb{1}(X_t = y) dt \right] \\
 &= \mathbb{E}_x \left[\sum_{n=0}^{H_x-1} \mathbb{1}(Y_n = y) S_{n+1} \right] \\
 &= \mathbb{E}_x \left[\sum_{n=0}^{\infty} S_{n+1} \mathbb{1}(Y_n = y, n \leq H_x - 1) \right] \\
 &= \sum_{n=0}^{\infty} \mathbb{E}_x [S_{n+1} | Y_n = y, n \leq H_x - 1] \mathbb{P}_x(Y_n = y, n \leq H_x - 1)
 \end{aligned}$$

Since $\{n < H_x\}^c = \{H_x \leq n\} \in \sigma\{Y_1, \dots, Y_n\}$ (i.e depends on Y_1, \dots, Y_n only) its a stopping time so the Strong Markov Property says

$$\begin{aligned}
 \mu^x(y) &= \sum_{n=0}^{\infty} \mathbb{E}_x [S_{n+1} | Y_n = y] \mathbb{P}_x(Y_n = y, n \leq H_x - 1) \\
 &= \sum_{n=0}^{\infty} \frac{1}{q_y} \mathbb{P}_x(Y_n = y, n \leq H_x - 1) \\
 &= \frac{1}{q_y} \sum_{n=0}^{\infty} \mathbb{E}_x [\mathbb{1}(Y_n = y, n \leq H_x - 1)] \\
 &= \frac{1}{q_y} \mathbb{E} \left[\sum_{n=0}^{\infty} \mathbb{1}(Y_n = y, n \leq H_x - 1) \right] \\
 &= \frac{1}{q_y} \mathbb{E}_x \left[\sum_{n=0}^{H_x-1} \mathbb{1}(Y_n = y) \right] \\
 &= \frac{\nu^x(y)}{q_y}.
 \end{aligned}$$

□

Definition. A recurrent state x is called *positive recurrent* if

$$m_x = \mathbb{E}_x T_x < \infty.$$

Otherwise, we call x *null recurrent*.

Theorem 2.11. Let $X \sim \text{Markov}(Q)$ be irreducible. Then the following are equivalent

- (a) Every state is positive recurrent;
- (b) Some state is positive recurrent;

(c) X is non-explosive and has an invariant distribution.

Also, when (c) holds, the invariant distribution λ is given by $\lambda(x) = \frac{1}{q_x m_x}$ for all x .

Proof. Clearly (a) \Rightarrow (b). Now we show (b) \Rightarrow (c). Assume without loss of generality that $q_x > 0$. Let x be a positive recurrent state. Then all states are recurrent, so Y is recurrent and the chain is non-explosive starting from any y . As Y is recurrent, ν^x is an invariant measure for Y . So $\mu^x = \frac{\nu^x}{q_y}$ (as defined previously) is an invariant measure for X . Also

$$\mu_x(y) = \mathbb{E}_x \left[\int_0^{T_x} \mathbb{1}(X_t = y) dt \right],$$

so

$$\begin{aligned} \sum_{y \in I} \mu^x(y) &= \mathbb{E}_x \left[\int_0^{T_x} \sum_{y \in I} \mathbb{1}(X_t = y) dt \right] \\ &= \mathbb{E}_x T_x < \infty. \end{aligned}$$

So μ_x is normalisable, and $\frac{\mu_x}{\mathbb{E}_x T_x}$ is an invariant distribution for X .

Now we show (c) \Rightarrow (a). By a previous lemma, the measure $\beta(y) = \lambda(y)q_y$ is an invariant measure for Y . Since $\sum_{y \in I} \lambda(y) = 1$, $\lambda(x) > 0$ for some x . Since Y is irreducible, for any $y \in I$, $x \rightarrow y$, i.e. $p_{xy}(n) > 0$ for some n . As β is invariant for Y , $\beta P^n = \beta$. So

$$\lambda(y)q_y = \beta y = \sum_{z \in I} \beta_z p_{zy}(n) \geq \beta_x p_{xy}(n) = \lambda(x)q_x p_{xy}(n) > 0$$

so $\lambda(y) > 0$ for all y . Fix some $x \in I$. Then $\lambda(x) > 0$ so define $a^x(y) = \frac{\beta(y)}{\lambda(x)q_x}$ for all $y \in I$, which is invariant for Y as a scalar multiple of $\beta(y)$, and $a^x(x) = 1$. By the theorem for discrete-time chains $a^x(y) \geq \nu^x(y)$ for all $y \in I$, where $\nu^x(y) = \mathbb{E}_x \left[\sum_{n=0}^{H_x-1} \mathbb{1}(Y_n = y) \right]$ and where $H_x = \inf\{n \geq 1 : Y_n = x\}$.

Also if $\mu^x(y) = \mathbb{E}_x \left[\int_0^{T_x} \mathbb{1}(X_t = y) dt \right]$ then $\mu^x(y) = \frac{\nu^x(y)}{q_y}$ and

$$\begin{aligned} \sum_{y \in I} \mu^x(y) &= \mathbb{E}_x \left[\int_0^{T_x} \sum_{y \in I} \mathbb{1}(X_t = y) dt \right] \\ &= \mathbb{E}_x T_x = m_x \quad (\text{as } X \text{ is non-explosive}) \end{aligned}$$

Then

$$\begin{aligned}
 \mu_x &= \sum_y \mu^x(y) = \sum_y \frac{\nu^x(y)}{q_y} \leq \sum_y \frac{a^x(y)}{q_y} \\
 &= \sum_y \frac{\beta(y)}{\lambda(x)q_xq_y} \\
 &= \sum_y \frac{\lambda(y)q_y}{\lambda(x)q_xq_y} \\
 &= \frac{1}{\lambda(x)q_x} \sum_y \lambda(y) \\
 &= \frac{1}{\lambda(x)q_x} < \infty.
 \end{aligned}$$

Hence x is positive recurrent. As x was arbitrary this means all states are positive recurrent.

Also, if (c) holds, then X is recurrent, so Y is recurrent. Hence $a^x(y) = v^x(y)$ for all y . Therefore $m_x = \frac{1}{\lambda(x)q_x}$ as the previous inequality becomes equality. \square

Example. On \mathbb{Z}^+ , suppose $q_{i,i+1} = \lambda q_i$, $q_{i,i-1} = \mu q_i$ and $q_{ii} = -(\lambda + \mu)q_i$ and $q_{i,j} = 0$ for all other j (an example of a Birth & Death process). We have transition probabilities $p_{i,i+1} = \frac{\lambda}{\lambda + \mu}$ and $p_{i,i-1} = \frac{\mu}{\lambda + \mu}$. Then $(\lambda/\mu)^i$ is an invariant measure for Y . Then $\pi_i = \frac{1}{q_i}(\lambda/\mu)^i$ is invariant for X . So if $q_i = 2^i$ and $\lambda = \frac{3\mu}{2}$, then $\pi_i = (3/4)^i$ is invariant for X . Also $\sum_{i=0}^{\infty} \pi_x < \infty$ so X has an invariant distribution. Since $\lambda > \mu$, the chain is transient for Y and so is transient for X . If X were non-explosive then by the previous theorem it would be positive recurrent, hence X must be explosive.

Lemma 2.12. *Let X be a continuous-time Markov chain. Fix $t > 0$ and set $Z_n = X_{nt}$. Then $(Z_n)_{n=0}^{\infty}$ is a discrete-time Markov chain. Then x is recurrent for X if and only if x is recurrent for Z .*

Proof. Example Sheet. □

Theorem 2.13. *Let $X \sim \text{Markov}(Q)$ be recurrent, irreducible and λ be a measure. Then $\lambda Q = 0$ if and only if $\lambda P(s) = \lambda$ for all $s > 0$.*

Proof. Any measure λ such that $\lambda Q = 0$ is unique up to scalar multiplication (by a theorem proved previously).

Any measure λ such that $\lambda P(s) = \lambda$ for all s is unique up to scalar multiplication. Indeed, fix $s = 1$ so $\lambda P(1) = \lambda$. Then $(X_n)_{n=0}^{\infty}$ is a discrete time chain with transition matrix $P(1)$, and is irreducible, recurrent by the previous lemma. It also has λ as an invariant measure, hence unique (up to scalar multiplication).

So it is enough to show $\mu^x Q = 0$ and $\mu^x P(s) = \mu^x$ for all s where $\mu^x(y) = \mathbb{E}_x \left[\int_0^{T_x} \mathbb{1}(X_t = y) dt \right]$.

Also $\mu^x(y) = \frac{\nu^x(y)}{q_y}$ and since X is recurrent, Y is recurrent so ν^x is an invariant measure for Y . So μ^x is an invariant measure for X , i.e $\mu^x Q = 0$.

Also, by the Strong Markov Property,

$$\mathbb{E}_x \left[\int_0^s \mathbb{1}(X_t = y) dt \right] = \mathbb{E}_x \left[\int_{T_x}^{T_x+s} \mathbb{1}(X_t = y) dt \right]. \quad (*)$$

Thus

$$\begin{aligned}
\mu^x(y) &= \mathbb{E}_x \left[\int_0^{T_x} \mathbb{1}(X_t = y) dt \right] \\
&= \mathbb{E}_x \left[\int_0^s \mathbb{1}(X_t = y) dt \right] + \mathbb{E}_x \left[\int_s^{T_x} \mathbb{1}(X_t = y) dt \right] \\
&= \mathbb{E}_x \left[\int_{T_x}^{T_x+s} \mathbb{1}(X_t = y) dt \right] + \mathbb{E}_x \left[\int_s^{T_x} \mathbb{1}(X_t = y) dt \right] \\
&= \mathbb{E}_x \left[\int_s^{T_x+s} \mathbb{1}(X_t = y) dt \right] \\
&= \mathbb{E}_x \left[\int_0^\infty \mathbb{1}(X_{u+s} = y, u < T_x) dy \right] \quad (\text{letting } t = u + s) \\
&= \int_0^\infty \mathbb{P}_x(X_{u+s} = y, u < T_x) du \\
&= \int_0^\infty \sum_{z \in I} \mathbb{P}_x(X_u = z, X_{u+s} = y, u < T_x) du \\
&= \sum_{z \in I} p_{zy}(s) \mathbb{E}_x \left[\int_0^{T_x} \mathbb{1}(X_u = z) dy \right] \\
&= \sum_{z \in I} \mu^x(z) p_{zy}.
\end{aligned}$$

i.e $\mu^x = \mu^x P(s)$. Since s was arbitrary, $\mu^x = \mu^x P(s)$ for all s . □

Convergence to Equilibrium

Lemma 2.14. *For the semigroup $P(t)$ and all $t \geq 0$, $h \geq 0$,*

$$|p_{xy}(t+h) - p_{xy}(t)| \leq 1 - e^{-q_x h} \leq q_x h.$$

Proof.

$$\begin{aligned}
 |p_{xy}(t+h) - p_{xy}(t)| &= \left| \sum_z p_{xz}(h)p_{zy}(t) - p_{xy}(t) \right| \\
 &= \left| \underbrace{\sum_{z \neq x} p_{xz}(h)p_{zy}(t)}_{\in [0, 1-p_{xx}(h)]} - \underbrace{p_{xy}(t)(1-p_{xx}(h))}_{\in [0, 1-p_{xx}(h)]} \right| \\
 &\leq 1 - p_{xx}(h) \\
 &= \mathbb{P}_x(X(h) \neq x) \\
 &\leq \mathbb{P}_x(J_1 \leq h) \\
 &= 1 - e^{-q_x h}
 \end{aligned}$$

□

Theorem 2.15. *Let $X \sim \text{Markov}(Q)$ be irreducible, non-explosive, and let λ be an invariant distribution. Then for all $x, y \in I$, $p_{xy}(t) \rightarrow \lambda(y)$ as $t \rightarrow \infty$.*

Proof. Fix $\varepsilon > 0$. Fix $h > 0$ such that $q_x h < \varepsilon/2$. Consider the discrete time Markov Chain $(Z_n) = (X_{nh})_{n \geq 0}$. Then (Z_n) is irreducible and aperiodic ($p_{xy}(h) > 0$ for all x, y by irreducibility). As X is positive recurrent (non-explosive and has invariant distribution), $\lambda P(h) = \lambda$, so λ is an invariant distribution for Z_n .

By a discrete-time Markov Chain result, for all x, y , $p_{xy}(nh) \rightarrow \lambda(y)$ as $n \rightarrow \infty$. Hence there exists n_0 such that for all $n \geq n_0$, $|p_{xy}(nh) - \lambda(y)| < \varepsilon/2$. Let $t \geq n_0 h$. Then there exists $n \geq n_0$ such that $nh \leq t < (n+1)h$. So

$$|p_{xy}(t) - p_{xy}(nh)| \leq q_x(t - nh) \leq q_x h < \varepsilon/2.$$

Thus for all $n \geq n_0 h$,

$$|p_{xy}(t) - \lambda(y)| \leq |p_{xy}(t) - p_{xy}(nh)| + |p_{xy}(nh) - \lambda(y)| < \varepsilon.$$

□

Ergodic Theory

Theorem 2.16. *Let $X \sim \text{Markov}(\lambda, Q)$ be irreducible. Then*

$$\frac{1}{t} \int_0^t \mathbb{1}(X_s = x) ds \rightarrow \frac{1}{q_x m_x} \text{ as } t \rightarrow \infty \text{ almost surely.}$$

If X is positive recurrent \mathcal{E} π is the unique invariant distribution and $f : I \rightarrow \mathbb{R}$ is bounded, then

$$\frac{1}{t} \int_0^t f(X_s) ds \rightarrow \sum_{x \in I} f(x) \pi(x)$$

Proof. Not given. □

Note. The second limit can be justified by

$$\begin{aligned} \frac{1}{t} \int_0^t f(X_s) ds &= \frac{1}{t} \int_0^t \sum_{x \in I} f(x) \mathbb{1}(X_s = x) ds \\ &= \sum_{x \in I} f(x) \left(\frac{1}{t} \int_0^t \mathbb{1}(X_s = x) ds \right) \\ &\rightarrow \sum_{x \in I} f(x) \pi(x). \end{aligned}$$

Reversibility

Theorem 2.17. *Let $X \sim \text{Markov}(Q)$ be irreducible and non-explosive with invariant distribution π . Let $X_0 \sim \pi$. Fix $T > 0$ and set $\hat{X}_t = X_{T-t}$ for $0 \leq t \leq T$. Then $\hat{X} \sim \text{Markov}(\hat{Q})$ and has invariant distribution π where $\hat{q}_{xy} = \pi(y) \frac{q_{yx}}{\pi(x)}$. Also \hat{Q} is irreducible and non-explosive (i.e $Z \sim \text{Markov}(\hat{Q})$ is non-explosive).*

Proof. Note that \hat{Q} is indeed a Q -matrix: $\hat{q}_{xy} \geq 0$ for all x, y and $\sum_y \hat{q}_{xy} = \frac{1}{\pi(x)} \sum_y \pi(y) q_{yx} = \frac{1}{\pi(x)} (\pi Q)_x = 0$. Also \hat{Q} is irreducible (as Q is). Also $(\pi \hat{Q})_y = \sum_x \pi(x) \hat{q}_{xy} = \sum_x \pi(y) q_{yx} = 0$, so π is invariant for \hat{Q} .

Now, let $0 = t_0 \leq t_1 \leq \dots \leq t_n = T$, $x_1, \dots, x_n \in I$, let $s_i = t_i - t_{i-1}$. Then

$$\begin{aligned} \mathbb{P}(\hat{X}_{t_0} = x_0, \dots, \hat{X}_{t_n} = x_n) &= \mathbb{P}(X_0 = x_n, \dots, X_{T-t_1} = x_1, X_T = x_0) \\ &= \pi(x_n) p_{x_n x_{n-1}}(s_n) \dots p_{x_1 x_0}(s_1). \end{aligned}$$

Define $\hat{p}_{xy}(t) = \frac{\pi(y)}{\pi(x)} p_{yx}(t)$ so

$$\begin{aligned} \pi(x_n) p_{x_n x_{n-1}}(s_n) \dots p_{x_1 x_0}(s_1) &= \pi(x_n) \hat{p}_{x_{n-1} x_n}(s_n) \frac{\pi(x_{n-1})}{\pi(x_n)} \dots \hat{p}_{x_0 x_1}(s_1) \frac{\pi(x_0)}{\pi(x_1)} \\ &= \pi(x_0) \hat{p}_{x_0 x_1}(s_1) \dots \hat{p}_{x_{n-1} x_n}(s_n). \end{aligned}$$

So \hat{X} is Markov with transition semigroup $(\hat{P}(t))_{t \geq 0}$. Need to show that $\hat{P}(t)$ is the minimal non-negative solution to the Kolmogorov backward equation with \hat{Q} , that is $(\hat{P}(t))' = \hat{Q} \hat{P}(t)$.

Indeed,

$$\begin{aligned} \hat{p}'_{xy}(t) &= \frac{\pi(x)}{\pi(y)} p'_{yx}(t) \\ &= \frac{\pi(y)}{\pi(x)} \sum_z p_{yz}(t) q_{zx} && \text{(Kolmogorov forward eq for } P) \\ &= \frac{\pi(y)}{\pi(x)} \sum_z \frac{\pi(z)}{\pi(y)} \hat{p}_{zy}(t) q_{yx} \\ &= \frac{1}{\pi(x)} \sum_z \pi(x) \hat{q}_{xz} \hat{p}_{zy}(t) \\ &= (\hat{Q} \hat{P})_{xy}. \end{aligned}$$

Suppose R is another solution to the Kolmogorov forward equation: $R'(t) = \hat{Q} R(t)$. Then defining $\bar{R}_{xy}(t) = \frac{\pi(y)}{\pi(x)} R_{yx}(t)$ then as before \bar{R} satisfies $\bar{R}'(t) = \bar{R}(t) Q$. But we know that P is the minimal solution to this, so \hat{P} is minimal for the forward equation.

Now we show \hat{Q} is non-explosive. Indeed, X is irreducible and non-explosive with invariant distribution π , so X is (positive) recurrent. Hence $\pi P(t) = \pi$ for all t . Thus

$$\sum_y \hat{p}_{xy}(t) = \frac{1}{\pi(x)} \sum_y \pi(y) p_{yx}(t) = \frac{1}{\pi(x)} (\pi P(t))_x = \frac{1}{\pi(x)} \pi(x) = 1.$$

So if $Z \sim \text{Markov}(\hat{Q})$

$$1 = \sum_y \hat{p}_{xy}(t) = \sum_y \mathbb{P}_x(Z_t = y) = \sum_y \mathbb{P}_x(Z_t = y, t < \zeta) = \mathbb{P}_x(t < \zeta).$$

i.e $\mathbb{P}_x(\zeta > t) = 1$ for all t , so $\mathbb{P}_x(\zeta = \infty) = 1$, i.e non-explosive. □

Definition. Let $X \sim \text{Markov}(Q)$. It is called *reversible* if for all $T > 0$, $(X_t)_{0 \leq t \leq T}$ and $(X_{T-t})_{0 \leq t \leq T}$ have the same distribution.

Definition. A measure λ and a Q -matrix Q are said to be in *detailed balance* if for all x, y

$$\lambda(x)q_{xy} = \lambda(y)q_{yx}.$$

Lemma 2.18. If Q and λ are in detailed balance, then λ is invariant for Q (i.e $\lambda Q = 0$).

Proof.

$$(\lambda Q)_y = \sum_x \lambda(x)q_{xy} = \lambda(y) \sum_x q_{yx} = 0$$

□

Remark. To find an invariant measure, check the detailed balance equation as a first step.

Lemma 2.19. *Let $X \sim \text{Markov}(Q)$ be irreducible, non-explosive and π a distribution with $X_0 \sim \pi$. Then π and Q are in detailed balance if and only if $(X_t)_{t \geq 0}$ is reversible.*

Proof. X is reversible if and only if $Q = \hat{Q}$ and π is an invariant distribution, where $\hat{q}_{xy} = \frac{\pi(y)}{\pi(x)} q_{yx}$. This happens iff π and Q are in detailed balance. \square

Definition. A birth and death chain X is a continuous time Markov chain on $\mathbb{N} = \{0, 1, \dots\}$ where for $x \geq 1$ $q_{x,x-1} = \mu_x$, $q_{x,x+1} = \lambda_x$, q_{xy} for all other y ; and $q_{01} = \lambda_0$, $q_{0,y} = 0$ for all $y \neq 1$.

Lemma 2.20. *A measure π is an invariant measure for a birth and death chain if and only if it solves the detailed balance equation.*

Proof. We already have one direction. So we show that if π is invariant it satisfies the detailed balance equation. Indeed, let π be an invariant measure for Q , i.e $\pi Q = 0$. So for all $j \geq 1$,

$$\begin{aligned} (\pi Q)_j &= 0 = \pi_{j-1} q_{j-1,j} + \pi_j q_{j,j} + \pi_{j+1} q_{j+1,j} \\ &= \pi_{j-1} \lambda_{j-1} + \pi_{j+1} \mu_{j+1} - \pi_j (\lambda_j + \mu_j). \end{aligned}$$

So

$$\pi_{j+1} \mu_{j+1} - \pi_j \lambda_j = \pi_j \mu_j - \pi_{j-1} \lambda_{j-1}. \quad (*)$$

For $j = 1$ $(*)$ becomes $\pi_1 \mu_1 - \pi_0 \lambda_0 = 0$. So using induction and plugging in to the RHS of $(*)$ we get

$$\pi_{j+1} \mu_{j+1} = \pi_j \lambda_j.$$

As required. \square

3 Queueing Theory

Queues are processes which can be modelled as customers arriving at a server and then departing.

Q: what is the equilibrium queue length (including customers being served)?

Q: What is the busy period?

Q: Time spent by a customer in the queue/waiting-time (including the service time)?

We use M/G/K notation. The ‘M’ stands for “Markovian arrival” - customers arrive according to a Poisson process of rate λ . The ‘G’ stands for “general distribution” - it is the (iid) service time distribution, if ‘M’ is used instead of ‘G’ this represents $\text{Exp}(\mu)$ service times. The ‘K’ stands for the number of servers ($k = 1$ or ∞).

Let X_t be the queue length at time t (including the customers being served). Then $(X_t)_{t \geq 0}$ is a continuous time process on state space $I = \{0, 1, 2, \dots\}$. If we have a M/M/1 or M/M/ ∞ process, then $(X_t)_{t \geq 0}$ is Markov and in particular it's a birth & death chain with

$$\begin{aligned} \text{M/M/1: } & q_{i,i+1} = \lambda, \quad q_{i,i-1} = \mu \\ \text{M/M}/\infty: & q_{i,i+1} = \lambda, \quad q_{i,i-1} = i\mu \end{aligned}$$

M/M/1:

Theorem 3.1. *Let $\rho = \lambda/\mu$. Then the queue length X (for a M/M/1 process) is transient if and only if $\rho > 1$, recurrent if and only if $\rho \leq 1$ and positive recurrent if and only if $\rho < 1$. In the positive recurrent case, the invariant distribution is*

$$\pi(n) = (1 - \rho)\rho^n, \quad n = 0, 1, \dots$$

And if $\rho < 1$, and $X_0 \sim \pi$, then the wait time (including service time) for a customer that arrives at time t is $\text{Exp}(\mu - \lambda)$.

Proof. The jump chain Y is given by $p_{i,i+1} = \lambda/(\lambda + \mu)$ and $p_{i,i-1} = \mu/(\lambda + \mu)$. This is just a biased SRW on \mathbb{N} (with reflection at 0). Thus Y (and hence X) is transient if $\lambda > \mu$, and recurrent if $\lambda \leq \mu$.

It is non-explosive since $\sup_i q_i = (\lambda + \mu) < \infty$. Thus we have positive recurrence iff there is an invariant distribution. Since X is a birth & death chain, a measure is invariant iff it satisfies detailed balance. Thus $\pi(n)\lambda = \pi(n+1)\mu$, i.e. $\pi(n+1) = \pi(n)(\lambda/\mu)^{n+1}$. So π is normalisable iff $\lambda/\mu = \rho < 1$. When $\rho < 1$, $\pi(n) = (1 - \rho)\rho^n$ is an invariant distribution. So π is the distribution of a (shifted) geometric random variable, i.e. π is the distribution of $Z - 1$ where $Z \sim \text{Geo}(1 - \rho)$.

If $\rho < 1$ and $X_0 \sim \pi$ then $X_t \sim \pi$ (as X is recurrent, π invariant iff $\pi P(t) = \pi$ for all t). So the wait time W of a customer arriving at time t is $W = \sum_{i=1}^{X_t+1} T_i$ where $T_i \sim \text{Exp}(\mu)$ are iid and independent of X_t . As $X_t + 1 \sim \text{Geo}(1 - \rho)$ is independent of $(T_i)_{i \geq 1}$ we have $W \sim \text{Exp}(\mu(1 - \rho)) = \text{Exp}(\mu - \lambda)$ (by Example Sheet 1).

We have expected queue length at equilibrium

$$\mathbb{E}_\pi X_t = \mathbb{E}_\pi Z - 1 = \frac{1}{1 - \rho} - 1 = \frac{\rho}{1 - \rho} = \frac{\lambda}{\mu - \lambda}.$$

□

M/M/ ∞ :

Theorem 3.2. *The queue length X_t is positive recurrent for all $\mu > 0$, $\lambda > 0$ with invariant distribution $\text{Poi}(\rho)$ where $\rho = \lambda/\mu$.*

Proof. As X is a birth & death process, we just solve the detailed balance equation:

$$\lambda\pi_{n-1} = n\mu\pi_n \implies \pi_n = \frac{1}{n} \frac{\lambda}{\mu} \pi_{n-1} = \dots = \frac{1}{n!} \left(\frac{\lambda}{\mu}\right)^n \pi_0.$$

This is always normalisable with $\pi_n = e^{-\lambda/\mu} (\lambda/\mu)^n \frac{1}{n!}$ i.e $\pi \sim \text{Poi}(\rho)$.

We will in fact show Y is positive recurrent. Define $\mu_i = \pi_i q_i$. Then μ is an invariant measure for Y . It is enough to check that μ is normalisable. We have

$$\mu_i = (i\mu + \lambda) e^{-\rho} \frac{\rho^i}{i!} = \rho\mu \left(e^{-\rho} \frac{\rho^{i-1}}{(i-1)!} (i + \rho) \right)$$

and

$$\sum_{i=0}^{\infty} \frac{\rho^{i-1}}{(i-1)!} (i + \rho) = \sum_{i=1}^{\infty} \frac{\rho^{i-1}}{(i-1)!} + \sum_{i=0}^{\infty} \frac{\rho^i}{i!} < \infty$$

so we are done. \square

Let A and D denote the arrival and departure processes associated with a queue (i.e A_t and D_t are the number of customers that have arrived/departed by time t respectively). A, D are increasing processes, and A increases by 1 if and only if X increases by 1; D increases by 1 if and only if X decreases by 1. So $X_t = X_0 + A_t - D_t$. A is a Poisson process of time λ .

Remark. A Poisson process does not have an invariant distribution, but still has the following time-reversing property: if N is a Poisson Process of rate λ , then for any $T > 0$, $\hat{N}_t = N_T - N_{T-t}$ is again a Poisson Process of rate λ on $[0, T]$. Indeed, conditioning on $N_T = n$, the distribution of the jump times is $\frac{n!}{T^n} \mathbb{1}(0 \leq t_1 \leq t_2 \leq \dots t_n \leq T)$.

Theorem 3.3 (Burke's Theorem). *Consider an M/M/1 queue with $\mu > \lambda > 0$ or an M/M/ ∞ queue with $\mu, \lambda > 0$. At equilibrium (i.e $X_0 \sim \pi$), D is a Poisson process of rate λ and X_t is independent of $(D_s : s \leq t)$.*

Remark. This roughly says that “the output of a stationary M/M/ k queue is again a Poisson process”.

Remark. $X_0 \sim \pi$ is essential. Suppose that $X_0 = 5$ for an M/M/1, the first departure happens at $\text{Exp}(\mu)$ and not $\text{Exp}(\lambda)$.

Remark. The processes $(X_s, s \leq t)$ and $(D_s : s \leq t)$ are not independent - clearly D has a jump of +1 exactly when X has a jump of -1.

Proof of Burke's Theorem. As X is a birth & death process, π satisfies the detailed balance equation, i.e if $X_0 \sim \pi$ then X is reversible. Thus for a fixed $T > 0$, with $\hat{X}_t = X_{T-t}$ we have $(\hat{X}_t)_{0 \leq t \leq T} \stackrel{d}{=} (X_t)_{0 \leq t \leq T}$. Hence the arrival process \hat{A} for \hat{X} (until time T) is a Poisson Process of rate λ . But $\hat{A}_t = D_T - D_{T-t}$.

Since the time reversal of a Poisson Process on $[0, T]$ is again a Poisson Process on $[0, T]$, this implies $(D_t)_{0 \leq t \leq T}$ is a Poisson Process of rate λ on $[0, T]$. Since $T > 0$ is arbitrary, this determines the finite-dimensional distributions of D and hence determines the distribution of D , i.e D is a Poisson Process of rate λ on \mathbb{R} .

Independence: as X_0 is independent of $(A_s : 0 \leq s \leq T)$, for the \hat{X} , \hat{X}_0 is independent of (\hat{A}_s) , i.e X_T is independent of $(D_t)_{0 \leq t \leq T}$. \square

Queues in tandem

Suppose that there is an M/M/1 queue with parameters λ and μ_1 . After a customer is served, they immediately join a second M/M/1 queue with parameters λ and μ_2 . Let X and Y denote the queue lengths of the two queues respectively. For (X, Y) have state space $I = \mathbb{N} \times \mathbb{N}$ and the rates are

$$(m, n) \rightarrow \begin{cases} (m+1, n) & \text{with rate } \lambda \\ (m-1, n+1) & \text{with rate } \mu_1 \text{ if } m \geq 1 \\ (m, n-1) & \text{with rate } \mu_2 \text{ if } n \geq 1 \end{cases}$$

Theorem 3.4. (X, Y) is positive recurrent if and only if $\lambda < \mu_1$ and $\lambda < \mu_2$. In this case, the invariant distribution is given by

$$\pi(m, n) = (1 - \rho_1)\rho_1^m(1 - \rho_2)\rho_2^n \text{ where } \rho_1 = \lambda/\mu_1, \rho_2 = \lambda/\mu_2.$$

i.e at equilibrium, X_t and Y_t are independent (for fixed t , not as processes).

Proof 1. Directly check that $\pi Q = 0$. As the rates are bounded, (X, Y) is non-explosive. \square

Proof 2. Note the marginal X is an M/M/1 queue. Thus X is positive recurrent if and only if $\lambda < \mu_1$ with invariant distribution $\pi^1(m) = (1 - \rho_1)\rho_1^m$. By Burke's theorem, if $X_0 \sim \pi^1$, then the departure process of the first queue is a Poisson Process of rate λ , which is the arrival process for the second queue.

So the second queue is M/M/1(λ, μ_2) with invariant distribution $\pi^2(n) = (1 - \rho_2)\rho_2^n$ if $\lambda < \mu_2$. If $X_0 \sim \pi^1$ and $Y_0 \sim \pi^2$ are independent, then $X_t \sim \pi^1$ (as X is recurrent) and also by Burke's theorem, X_t is independent of the departure process until time t , and also independent of Y_0 , so X_t is independent of Y_t .

Also $Y_t \sim \pi^2$ (as Y is recurrent), so $(X_t, Y_t) \sim \pi$. i.e $(X_0, Y_0) \sim \pi \Rightarrow (X_t, Y_t) \sim \pi$ for all t . So π is invariant for (X, Y) (by the following exercise). \square

Exercise: if Z is irreducible, π a distribution and $\pi P(t) = \pi$ for all t , then π is invariant for Z (consider the discrete-time chain $Z_n = (Z_n)$).

Jackson's Network

Have a network of N single-server queues with arrival rates λ_k and service rates μ_k , $1 \leq k \leq N$. After service, each customer in queue i moves to queue j with probability p_{ij} , or exits the system with probability $p_{i0} = 1 - \sum_{j=1}^N p_{ij}$.

We assume $p_{ii} = 0$ and $p_{i0} > 0$ for all $1 \leq i \leq N$. Also assume the system is irreducible, i.e a customer arriving in queue i has a positive probability of visiting queue j at a later time for all $i \neq j$. Thus $I = \{0, 1, 2, \dots\}^N$, where if $x = (x_1, \dots, x_N)$ then x_i is the number of customers in queue i .

If $n = (n_1, \dots, n_N) \in I$ and $e_i = (0, \dots, 0, 1, 0, \dots, 0)$ has all entries 0 except i th entry 1, then

$$\begin{aligned} q_{n, n+e_i} &= \lambda_i \text{ for } i = 1, 2, \dots, N \\ q_{n, n-e_i+e_j} &= \mu_i p_{ij} \text{ for } i, j = 1, \dots, N, n_i \geq 1, i \neq j \\ q_{n, n-e_i} &= \mu_i p_{i0} \text{ for } i = 1, \dots, N, n_i \geq 1 \end{aligned}$$

Definition. We say a vector $\bar{\lambda} = (\bar{\lambda}_1, \dots, \bar{\lambda}_N)$ satisfies the *traffic equation* if for all $1 \leq i \leq N$

$$\bar{\lambda}_i = \lambda_i + \sum_{\substack{j=1 \\ j \neq i}}^N \bar{\lambda}_j p_{ji}. \quad (*)$$

Remark. $\bar{\lambda}_i$ is the “effective arrival rate” at queue i .

Lemma 3.5. *There exists a unique solution to (*).*

Proof. Uniqueness: see Example sheet 3.

Existence: let $p_{00} = 1$. Then $P = (p_{ij})_{i,j=0}^N$ is a stochastic matrix corresponding to a discrete-time Markov chain (Z_n) . Then (Z_n) is absorbing at 0, so the communicating class $\{1, \dots, N\}$ is not closed, so is transient. Thus if $V_i = \# \text{visits to state } i \text{ by } Z$, then starting from Z_0 , $\mathbb{E}V_i < \infty$ for all $i = 1, \dots, N$.

Let $\mathbb{P}(Z_0 = i) = \frac{\lambda_i}{\lambda}$, for $i = 1, \dots, N$, $\lambda = \sum_{i=1}^N \lambda_i$. Then for all $1 \leq i \leq N$

$$\begin{aligned} \mathbb{E}V_i &= \mathbb{E} \sum_{n=0}^{\infty} \mathbb{1}(Z_n = i) \\ &= \mathbb{P}(Z_0 = i) + \sum_{n=0}^{\infty} \mathbb{P}(Z_{n+1} = i) \\ &= \mathbb{P}(Z_0 = i) + \sum_{n=0}^{\infty} \sum_{j=1}^N \mathbb{P}(Z_n = j) p_{ji} \\ &= \frac{\lambda_i}{\lambda} + \sum_{j=1}^N p_{ji} \sum_{n=0}^{\infty} \mathbb{P}(Z_n = j) \\ &= \frac{\lambda_i}{\lambda} + \sum_{j=1}^N p_{ji} \mathbb{E}V_j \end{aligned}$$

Multiplying throughout by λ and setting $\bar{\lambda}_i = \lambda \mathbb{E}V_i$ we get $\bar{\lambda}_i = \lambda_i + \sum_{j=1}^N \bar{\lambda}_j p_{ji}$. \square

Theorem 3.6 (Jackson, 1957). *Assume that the traffic equation (*) has solution $\bar{\lambda}_i$ such that $\bar{\lambda}_i < \mu_i$ for all $i = 1, \dots, N$. Then the Jackson Network is positive recurrent with invariant distribution*

$$\pi(n) = \prod_{i=1}^N (1 - \bar{\rho}_i) \bar{\rho}_i^{n_i}, \text{ where } \bar{\rho}_i = \frac{\bar{\lambda}_i}{\mu_i}.$$

At equilibrium, the departure processes (to outside) from each queue form independent Poisson processes with rates $\bar{\lambda}_i p_{i0}$.

Remark. At equilibrium, the queue lengths X_t^i are independent for a fixed time t .

Remark. The equilibrium for Jackson Network is not reversible, but there is “partial reversibility”.

Lemma 3.7 (Partial detailed balance). *Let X be a Markov process on I and π be a measure on I . Assume that for each $x \in I$, there is a partition of $I \setminus \{x\}$ as*

$$I \setminus \{x\} = I_1^x \cup I_2^x \cup \dots$$

such that for all $i \geq 1$

$$\sum_{y \in I_i^x} \pi(x) q_{xy} = \sum_{y \in I_i^x} \pi(y) q_{yx}.$$

If π satisfies this, then π is an invariant measure.

Proof. We show $\pi Q = 0$:

$$\begin{aligned} (\pi Q)_y &= \sum_x \pi(x) q_{xy} = \sum_{x \neq y} \pi(x) q_{xy} + \pi(y) q_{yy} \\ &= \sum_i \sum_{x \in I_i^y} \pi(x) q_{xy} + \pi(y) q_{yy} \\ &= \sum_i \sum_{x \in I_i^y} \pi(y) q_{yx} + \pi(y) q_{yy} \\ &= \sum_x \pi(y) q_{yx} \\ &= 0. \end{aligned}$$

□

We are now ready to prove

Theorem 3.8 (Jackson, 1957). *Assume that the traffic equation (*) has solution $\bar{\lambda}_i$ such that $\bar{\lambda}_i < \mu_i$ for all $i = 1, \dots, N$. Then the Jackson Network is positive recurrent with invariant distribution*

$$\pi(n) = \prod_{i=1}^N (1 - \bar{\rho}_i) \bar{\rho}_i^{n_i}, \text{ where } \bar{\rho}_i = \frac{\bar{\lambda}_i}{\mu_i}.$$

At equilibrium, the departure processes (to outside) from each queue form independent Poisson processes with rates $\bar{\lambda}_i p_{i0}$.

Proof. Let $\pi(n) = \prod_{i=1}^N \bar{\rho}_i^{n_i}$. We shall check this satisfies the partial detailed balance equations. Let $A = \{e_i : 1 \leq i \leq N\}$, $D_j = \{e_i - e_j : i \neq j\} \cup \{-e_j\}$ where $e_i = (0, \dots, 0, 1, 0, \dots, 0)$ has all entries 0 except i th entry 1.

When a customer arrives and $n \in I$, $n \rightarrow n + m$ for some $m \in A$. When a customer leaves queue j , $n \rightarrow n + d$ for some $m \in D_j$. Fix n , consider the partition of $I \setminus \{n\}$ given by

$$I \setminus \{n\} = \{n + A\} \cup \bigcup_{j=1}^N \{n + D_j\}.$$

We will show

$$\begin{aligned}\sum_{m \in A} q_{n,n+m} &= \sum_{m \in A} \frac{\pi_{n+m}}{\pi_n} q_{n+m,n}, \\ \sum_{m \in D_j} \pi_n q_{n,n+m} &= \sum_{m \in D_j} \frac{\pi_{n+m}}{\pi_n} q_{n+m,n}.\end{aligned}$$

Note

$$\sum_{m \in D_j} q_{n,n+m} = \mu_j p_{j0} + \sum_{i \neq j} \mu_j p_{ji} = \mu_j$$

and

$$\begin{aligned}\sum_{m \in D_j} \frac{\pi_{n+m}}{\pi_n} q_{n+m,n} &= \frac{\pi_{n-e_j}}{\pi_n} q_{n-e_j,n} + \sum_{i \neq j} \frac{\pi_{n+e_i-e_j}}{\pi_n} q_{n+e_i-e_j,n} \\ &= \frac{1}{\bar{\rho}_j} \lambda_j + \sum_{i \neq j} \frac{\bar{\rho}_i}{\bar{\rho}_j} \mu_i p_{ij} \\ &= \frac{\lambda_j}{\bar{\rho}_j} + \sum_{i \neq j} \frac{\bar{\lambda}_i}{\bar{\rho}_j} p_{ij} \\ &= \frac{\lambda_j + \sum_{i \neq j} \bar{\lambda}_i p_{ij}}{\bar{\rho}_j} \\ &= \frac{\bar{\lambda}_j}{\bar{\rho}_j} \\ &= \mu_j.\end{aligned}$$

Now for A :

$$\sum_{m \in A} q_{n,n+m} = \sum_i \lambda_i$$

and

$$\begin{aligned}\sum_{m \in A} \frac{\pi_{n+m}}{\pi_n} q_{n+m,n} &= \sum_i \frac{\pi_{n+e_i}}{\pi_n} q_{n+e_i,n} = \sum_i \frac{\bar{\lambda}_i}{\mu_i} \mu_i p_{i0} \\ &= \sum_i \bar{\lambda}_i p_{i0} \\ &= \sum_i \bar{\lambda}_i \left(1 - \sum_j p_{ij}\right) \\ &= \sum_i \bar{\lambda}_i - \sum_j \sum_i p_{ij} \bar{\lambda}_i \\ &= \sum_i \bar{\lambda}_i - \sum_j (\bar{\lambda}_j - \lambda_j) \\ &= \sum_i \lambda_i.\end{aligned}$$

Finally as the rates are bounded, it is non-explosive, hence positive recurrent. (Final part of theorem is on the Example Sheet). \square

M/G/1 queue:

Arrival: Poisson process of rate λ . Service time of n th customer: $\xi_n \geq 0$ and (ξ_n) iid with $\mathbb{E}\xi_1 = \frac{1}{\mu}$. Single server.

Denote by $(X_t)_{t \geq 0}$ the queue length, which is no longer a Markov process (service time is no longer memoryless in general).

Let D_n be the departure time of the n th customer. We consider the discrete-time process $Z_n = X(D_n)$.

Proposition 3.9. $Z_n = X(D_n)$, $n = 0, 1, \dots$ is a discrete-time Markov chain with transition matrix

$$\begin{pmatrix} p_0 & p_1 & p_2 & \dots \\ p_0 & p_1 & p_2 & \dots \\ 0 & p_0 & p_1 & p_2 & \dots \\ 0 & 0 & p_0 & p_1 & \dots \\ \vdots & \ddots & \ddots & \ddots & \dots \end{pmatrix}$$

where $p_k = \mathbb{E} \left[e^{-\lambda \xi_1} \frac{(\lambda \xi_1)^k}{k!} \right]$ for $k = 0, 1, \dots$

Proof. Let A_{n+1} be the number of customers arriving after time D_n and during the service time of the $(n+1)$ th customer ξ_{n+1} . Then the A_n are iid (by the independent increment property of a Poisson process), and given ξ_n , $A_n \sim \text{Poi}(\lambda \xi_n)$, i.e. $\mathbb{P}(A_k = k) = \mathbb{E}[\mathbb{P}(A_k = k | \xi_k)] = \mathbb{E} \left[e^{-\lambda \xi_n} \frac{(\lambda \xi_n)^k}{k!} \right] = p_k$.

Now

$$X(D_{n+1}) = \begin{cases} A_{n+1} & \text{if } X(D_n) = 0 \\ X(D_n) + A_{n+1} - 1 & \text{if } X(D_n) > 0 \end{cases}$$

so we have the required transition matrix. \square

Lemma 3.10. Let (Y_i) be iid integer valued random variables and let $S_n = Y_1 + \dots + Y_n$ be the corresponding random walk on \mathbb{Z} starting from 0. If $\mathbb{E}|Y_1| < \infty$, then S is recurrent if and only if $\mathbb{E}Y_1 = 0$.

Proof. Not given. \square

Theorem 3.11. Let $\rho = \frac{\lambda}{\mu}$. If $\rho \leq 1$, the queue is recurrent in the sense that it will hit 0 almost surely. If $\rho > 1$ then it is transient in the sense that there is a positive probability the queue length will never hit 0.

Proof 1. X is transient/recurrent in the sense of the theorem $\iff X(D_n)$ is transient/recurrent in the usual sense. While $X(D_n) > 0$, $(X(D_n))$ is a random walk on \mathbb{Z} with step distribution $Y_i = A_i - 1$. But

$$\mathbb{E}Y_1 = \mathbb{E}A_1 - 1 = \mathbb{E}[\mathbb{E}[A_1|\xi_1]] - 1 = \mathbb{E}[\lambda\xi_1] - 1 = \frac{\lambda}{\mu} - 1 = \rho - 1.$$

If $\rho = 1$ then X is recurrent (by the previous lemma). If $\rho < 1$, then X has a drift to the left, so recurrent. If $\rho > 1$ then X is transient. \square

Proof 2. We will use a hidden branching structure. Say that a customer C_2 is an offspring of C_1 if C_2 arrives during the service of C_1 . This defines a tree. The offspring distribution is iid and distributed as A_1 which given ξ_1 is $\text{Poi}(\lambda\xi_1)$. We have $\mathbb{E}A_1 = \mathbb{E}\mathbb{E}[A_1|\xi_1] = \mathbb{E}[\lambda\xi_1] = \lambda\mathbb{E}\xi_1 = \frac{\lambda}{\mu} = \rho$.

This is a branching process, and we have recurrence (e.g the queue empties out almost surely) if and only if the tree is finite with probability 1, which happens if and only if $\mathbb{E}A_1 = \rho \leq 1$ (see IA Probability). \square

Definition. The time between a customer joining the queue and a customer departing leaving behind an empty queue is called the *busy period*.

Proposition 3.12. *For the M/G/1 queue with $\lambda < \mu$, the length of the busy period B satisfies*

$$\mathbb{E}B = \frac{1}{\mu - \lambda}.$$

Proof. Exercise: use the branching process structure from above. \square

Lemma 3.13. *Let $(Y_i)_{i \geq 1}$ be iid \mathbb{Z} -valued random variables and let $S_n = Y_1 + \dots + Y_n$ be the corresponding random walk starting from 0. If $\mathbb{E}|Y_1| < \infty$, then S is recurrent if and only if $\mathbb{E}Y_1 = 0$.*

Proof. By the Strong Law of Large Numbers, if $\mathbb{E}Y_1$ exists and is non-zero, $|S_n| \rightarrow \infty$ almost surely.

If $\mathbb{E}Y_1 = 0$ then by the Strong Law of Large Numbers $S_n/n \rightarrow 0$ almost surely. Fix $\varepsilon > 0$. Then for some n large enough

$$\min_{i \leq n} \mathbb{P}(|S_i| \leq \varepsilon n) \geq 1/2. \quad (*)$$

Indeed, choose N_1 large so that for all $n \geq N_1$ have $\mathbb{P}(|S_n| \leq \varepsilon n) \geq 1/2$. Then choose $N_2 > N_1$ large enough so that $\mathbb{P}(|S_i| \leq \varepsilon N_2) \geq 1/2$ for all $i = 1, \dots, N_1 - 1$. Then for $n = N_2$ it holds.

Let

$$\begin{aligned} G_n(x) &= \mathbb{E}_0[\text{\#visits to } x \text{ by time } n] = \mathbb{E}_0 \left[\sum_{k=0}^{\infty} \mathbb{1}(S_k = x) \right] \\ &= \sum_{k=0}^n \mathbb{P}_0(S_k = x). \end{aligned}$$

Clearly, $G_n(x)$ is increasing in n , and for all x , $G_n(x) \leq G_n(0)$ since

$$G_n(x) = \sum_{k=0}^n \mathbb{P}_0(T_x = k) G_{n-k}(0) \leq G_n(0) \sum_{k=0}^n \mathbb{P}_0(T_x = k) \leq G_n(0).$$

Thus taking n as in $(*)$,

$$\begin{aligned}
 (2n\varepsilon + 1)G_n(0) &\geq \sum_{|x| \leq n\varepsilon} G_n(x) = \sum_{|x| \leq n\varepsilon} \sum_{k=0}^n \mathbb{P}(S_k = x) \\
 &= \sum_{k=0}^n \sum_{|x| \leq n\varepsilon} \mathbb{P}(S_k = x) \\
 &= \sum_{k=0}^n \mathbb{P}(|S_k| \leq n\varepsilon) \\
 &\geq \frac{n+1}{2}.
 \end{aligned}$$

So $G_n(0) \geq \frac{1}{4\varepsilon}$, and letting $n \rightarrow \infty$ $\mathbb{E}_0 V_0 \geq \frac{1}{4\varepsilon}$, and since $\varepsilon > 0$ was arbitrary, $\mathbb{E}_0 V_0 = \infty$ so we have recurrence. \square

4 Renewal Processes

Suppose buses arrive every 10 minutes on average, according to a Poisson process of rate $1/10$. How long does one need to wait on average if I arrive at time t ?

What is the “inter-arrival time” that contains t ? It is no longer $\text{Exp}(1/10)$, but larger.

What happens when the n th bus arrives after time ξ_n , where $\xi_n \geq 0$ is iid. Again the length of the interval containing t is larger than ξ_1 . In fact for t large enough, this is the “size-biased” distribution of ξ_1 .

Definition. Let $(\xi_i)_{i \geq 1}$ be iid non-negative random variables, distributed as ξ , with $\mathbb{P}(\xi > 0) > 0$. Set $T_n = \sum_{i=1}^n \xi_i$ and $N_t = \max\{n \geq 0 : T_n \leq t\}$ (the number of renewals until time t for ξ_n the time of the n th renewal). The process $(N_t : t \geq 0)$ is called a *renewal process*.

Remark. If ξ_1, ξ_2, \dots are iid $\text{Exp}(\lambda)$ then (N_t) is a Poisson process of rate λ .

Theorem 4.1. If $\mathbb{E}\xi = \frac{1}{\lambda} < \infty$ then as $t \rightarrow \infty$,

$$\frac{N_t}{t} \rightarrow \lambda \text{ almost surely, and } \frac{\mathbb{E}N_t}{t} \rightarrow \lambda.$$

Remark. We won’t prove $\frac{\mathbb{E}N_t}{t} \rightarrow \lambda$ (see Grimett-Strizakel).

Proof. First note that $N_t < \infty$ almost surely and $N_t \rightarrow \infty$ almost surely. Then $T_{N_t} \leq t \leq T_{N_t+1}$. Hence

$$\frac{T_{N_t}}{N_t} \leq \frac{t}{N_t} \leq \frac{T_{N_t+1}}{N_t}.$$

By the Strong Law of Large Numbers, $\frac{T_n}{n} \rightarrow \mathbb{E}\xi = \frac{1}{\lambda}$ and $N_t \rightarrow \infty$ as $t \rightarrow \infty$ almost surely, so $\frac{T_{N_t}}{N_t} \rightarrow \frac{1}{\lambda}$ almost surely and $\frac{T_{N_t+1}}{N_t} = \frac{T_{N_t+1}}{N_t+1} \frac{N_t+1}{N_t} \rightarrow \frac{1}{\lambda}$ almost surely. Thus $\frac{t}{N_t} \rightarrow \frac{1}{\lambda}$ almost surely. \square

Size-biased picking

Now suppose $\mathbb{P}(\xi_1 > 0) = 1$. Let $S_i = \xi_1 + \dots + \xi_i$, $1 \leq i \leq n$. Use S_i/S_n , $1 \leq i \leq n$ to produce a partition of $[0, 1]$ into n subintervals of lengths $Y_i = \xi_i/S_n$. Let U be a uniform $[0, 1]$ random variable independent of ξ_1, \dots, ξ_n , and let \hat{Y} denote the length of the interval containing U .

Since Y_1, \dots, Y_n are identically distributed and $\mathbb{E}[Y_1 + \dots + Y_n] = 1$ so $\mathbb{E}[Y_i] = 1/n$ for all i . What is the distribution of \hat{Y} ? It is not the same as Y_1 since U tends to fall in bigger intervals.

Proposition 4.2. $\mathbb{P}(\hat{Y} \in dy) = ny\mathbb{P}(Y_1 \in dy)$. Formally, $f_{\hat{Y}}(y) \propto yf_{Y_1}(y)$.

Proof.

$$\begin{aligned} \mathbb{P}(\hat{Y} \in dy) &= \sum_{i=1}^n \mathbb{P}\left(\hat{Y} \in dy, \frac{S_{i-1}}{S_n} \leq U \leq \frac{S_i}{S_n}\right) \\ &= \sum_{i=1}^n \mathbb{P}\left(\frac{\xi_i}{S_n} \in dy, \frac{S_{i-1}}{S_n} \leq U \leq \frac{S_i}{S_n}\right) \\ &= \sum_{i=1}^n \mathbb{P}\left(\frac{S_{i-1}}{S_n} \leq U \leq \frac{S_i}{S_n}\right) \mathbb{P}\left(\frac{\xi_i}{S_n} \in dy\right) \\ &= \sum_{i=1}^n y \mathbb{P}\left(\frac{\xi_i}{S_n} \in dy\right) \\ &= ny \mathbb{P}\left(\frac{\xi_1}{S_n} \in dy\right) \\ &= ny \mathbb{P}(Y_1 \in dy). \end{aligned}$$

□

Definition. Let X be a non-negative random variable with distribution μ and $\mathbb{E}X = m < \infty$. Then the *size-biased distribution* of μ is $\hat{\mu}(dy) = \frac{y\mu(dy)}{m}$. We write \hat{X} for a random variable with distribution $\hat{\mu}$.

Remark. $\mathbb{E}\hat{X} = \frac{\mathbb{E}X^2}{\mathbb{E}X} \geq \mathbb{E}X$ if $\mathbb{E}X^2 < \infty$.

Examples.

1. If $X \sim U((0, 1))$ then \hat{X} has distribution $\hat{\mu}(dx) = 2xdx$ on $[0, 1]$.
2. If $X \sim \text{Exp}(\lambda)$ then $\hat{\mu}(dx) = \frac{1}{1/\lambda} \lambda e^{-\lambda x} dx = \lambda^2 x e^{-\lambda x}$ so $\hat{X} \sim \Gamma(2, \lambda)$, i.e. \hat{X} has the same distribution as $X_1 + X_2$ where X_1, X_2 are iid copies of X .

Equilibrium theory of renewal processes

Given a renewal process $(N_t)_{t \geq 0}$ and a time $t > 0$, define

$A(t) = t - T_{N_t}$ the *age process* (time since last renewal)

$E(t) = T_{N_t+1} - t$ the *excess/residual life* (time until next renewal)

$L(t) = T_{N_t+1} - T_{N_t} = A(t) + E(t)$ the length of the current renewal.

What is the distribution of $L(t)$ for t large? Not ξ , but a size-biasing occurs: a big renewal interval is more likely to contain t .

Definition. A random variable is called *arithmetic* if $\mathbb{P}(\xi \in k\mathbb{Z}) = 1$ for some $k > 1$, $k \in \mathbb{Z}$, and *non-arithmetic* if it is not arithmetic, i.e for all $k > 1$, $\mathbb{P}(\xi \in k\mathbb{Z}) < 1$.

Theorem 4.3. Let ξ be non-arithmetic and let $\hat{\xi}$ have the size-biased distribution of ξ . Let $\mathbb{E}\xi = \frac{1}{\lambda}$. Then

$$(L(t), E(t)) \xrightarrow{d} (\hat{\xi}, U\hat{\xi})$$

where $U \sim U((0, 1])$ is independent of $\hat{\xi}$. Similarly

$$(L(t), A(t)) \xrightarrow{d} (\hat{\xi}, U\hat{\xi}).$$

i.e $\mathbb{P}(L(t) \leq x, E(t) \leq y) \rightarrow \mathbb{P}(\hat{\xi} \leq x, U\hat{\xi} \leq y)$ for all x, y .

Remark. $L(t)$ for large t has the size-biased distribution $\hat{\xi}$ and given $L(t)$, the point t falls uniformly within the renewal interval.

Remark. $\mathbb{P}(U\hat{\xi} \leq y) = \lambda \int_0^y \mathbb{P}(\xi > z) dz$. Indeed,

$$\begin{aligned} \mathbb{P}(U\hat{\xi} \leq y) &= \int_0^1 \mathbb{P}(\hat{\xi} \leq y/u) du = \int_0^1 \int_0^{y/u} \mathbb{P}(\hat{\xi} \in dx) du \\ &= \int_0^1 \int_0^{y/u} \lambda x \mathbb{P}(\xi \in dx) du \\ &= \int_0^\infty \lambda x \mathbb{P}(\xi \in dx) \int_0^{y/x \wedge 1} du \\ &= \int_0^\infty \lambda (x \wedge y) \mathbb{P}(\xi \in dx). \end{aligned}$$

Again,

$$\begin{aligned} \lambda \int_0^y \mathbb{P}(\xi > z) dz &= \lambda \int_0^y \int_z^\infty \mathbb{P}(\xi \in dx) dz \\ &= \lambda \int_0^\infty \mathbb{P}(\xi \in dx) \int_0^{x \wedge y} dz \\ &= \lambda \int_0^\infty (x \wedge y) \mathbb{P}(\xi \in dx). \end{aligned}$$

As required.

Example. If $\xi \in \text{Exp}(\lambda)$, then $\hat{\xi} \sim \Gamma(2, \lambda)$ and $\mathbb{P}(U\hat{\xi} \leq y) = \lambda \int_0^y \mathbb{P}(\xi > z)dz = \lambda \int_0^y e^{-\lambda z} dz = 1 - e^{-\lambda y}$ so $U\hat{\xi} \sim \text{Exp}(\lambda)$. Indeed, $E_t \sim \text{Exp}(\lambda)$ for all t .

Example. $\xi \in U((0, 1))$ and $E_t \xrightarrow{d} E_\infty$, then for $0 \leq y \leq 1$,

$$\begin{aligned}\mathbb{P}(E_\infty \leq y) &= \lambda \int_0^y \mathbb{P}(\xi > z)dz \\ &= 2 \int_0^y (1 - z)dz = 2 \left(y - \frac{y^2}{2} \right).\end{aligned}$$

Now we prove

Theorem 4.4. *Let ξ be non-arithmetic and let $\hat{\xi}$ have the size-biased distribution of ξ . Let $\mathbb{E}\xi = \frac{1}{\lambda}$. Then*

$$(L(t), E(t)) \xrightarrow{d} (\hat{\xi}, U\hat{\xi})$$

where $U \sim U((0, 1])$ is independent of $\hat{\xi}$. Similarly

$$(L(t), A(t)) \xrightarrow{d} (\hat{\xi}, U\hat{\xi}).$$

i.e $\mathbb{P}(L(t) \leq x, E(t) \leq y) \rightarrow \mathbb{P}(\hat{\xi} \leq x, U\hat{\xi} \leq y)$ for all x, y .

Proof. We only prove the theorem for ξ discrete, i.e ξ takes values in $\{1, 2, \dots\}$ and time is discrete.

First we prove the convergence for $(E(t))$. $(E(t) : t = 0, 1, \dots)$ is a discrete-time Markov chain on $I = \{1, 2, 3, \dots\}$ with transition probabilities $p_{i,i-1} = 1$ for $i \geq 2$ and $p_{1,n} = \mathbb{P}(\xi = n)$ for all $n \geq 1$.

$(E(t))$ is irreducible, recurrent, and aperiodic (as ξ is non-arithmetic). To get an invariant distribution we solve $\pi = \pi P$, i.e

$$\pi_n = \pi_{n+1} + \pi_1 \mathbb{P}(\xi = n) \quad \forall n \geq 1.$$

hence $\pi_1 = \pi_2 + \pi_1 \mathbb{P}(\xi = 1)$ so $\pi_2 = \pi_1 \mathbb{P}(\xi > 1)$. Then $\pi_2 = \pi_3 + \pi_1 \mathbb{P}(\xi = 2)$, so $\pi_3 = \pi_1 \mathbb{P}(\xi > 2)$. By induction, $\pi_n = \pi_1 \mathbb{P}(\xi > n - 1)$.

Since $\sum_{n \geq 1} \mathbb{P}(\xi > n - 1) = \mathbb{E}\xi = \frac{1}{\lambda}$ we get $\pi_n = \lambda \mathbb{P}(\xi > n - 1)$ for all $n \geq 1$. Thus, $\mathbb{P}(E(t) = y) \rightarrow \pi(y)$ for all $y \geq 1$ (since the chain is irreducible, aperiodic, positive recurrent). Hence for any integer,

$$\mathbb{P}(E(t) \leq y) \rightarrow \sum_{i=1}^y \pi_i = \lambda \sum_{i=1}^y \mathbb{P}(\xi > i - 1) = \lambda \int_0^y \mathbb{P}(\xi > x) dx.$$

Now $((L(t), E(t)) : t \geq 0)$ is also a discrete Markov chain on $I = \{(n, k) : 1 \leq k \leq n\} \subseteq \mathbb{N}^2$ with transition probabilities $p_{(n,k) \rightarrow (n,k-1)} = 1$ for $k \geq 2$, $p_{(n,1) \rightarrow (k,k)} = \mathbb{P}(\xi = k)$ for $k \geq 1$ (which is independent of n). This chain is again irreducible, recurrent, aperiodic, with invariant measure satisfying

$$\pi(n, k - 1) = \pi(n, k) \quad \forall 2 \leq k \leq n \text{ and}$$

$$\pi(k, k) = \underbrace{\sum_{m=1}^{\infty} \pi(m, 1)}_C \mathbb{P}(\xi = k).$$

Then $\pi(n, k) = C \mathbb{P}(\xi = n)$. Since

$$1 = \sum_{n=1}^{\infty} \sum_{k=1}^n \pi(n, k) = \sum_{n=1}^{\infty} C n \mathbb{P}(\xi = n) = C \mathbb{E}(\xi) = \frac{C}{\lambda}$$

have

$$\pi(n, k) = \lambda \mathbb{P}(\xi = n) = \underbrace{\lambda n \mathbb{P}(\xi = n)}_{\mathbb{P}(\hat{\xi}=n)} \underbrace{\frac{1}{n} \mathbb{1}_{\{1 \leq k \leq n\}}}_{\substack{\text{Given } \hat{\xi}=n, E_\infty \text{ is} \\ \text{uniform on } \{1, 2, \dots, n\}}}$$

and $\mathbb{P}(L(t) \leq x, E(t) \leq y) \rightarrow \sum_{n \leq x} \sum_{k \leq y} \pi(n, k)$. \square

Remark. In fact, for any fixed $t > 0$

$$\mathbb{P}(L(t) \geq x) \geq \mathbb{P}(\xi \geq x), \quad \forall x$$

i.e $L(t)$ *stochastically dominates* ξ and hence $\mathbb{E}L(t) \geq \mathbb{E}\xi$. This is called the ‘inspection paradox’.

Renewal-reward process

On top of the renewal structure, suppose there is a reward associated to each renewal, which could be a function of the renewal.

Let (ξ_i, R_i) be iid pairs of random variables (where ξ_i and R_i need not be independent) with $\xi \geq 0$ and $\mathbb{E}\xi = \frac{1}{\lambda} < \infty$. Let $(N_t)_{t \geq 0}$ be the renewal process associated with the ξ_i and let

$$R(t) = \sum_{i=1}^{N_t} R_i$$

be the total reward up to time t . Then

Proposition 4.5. *If $\mathbb{E}|R| < \infty$, as $t \rightarrow \infty$*

$$\frac{R(t)}{t} \rightarrow \lambda \mathbb{E}R \text{ almost surely, and } \frac{\mathbb{E}R(t)}{t} \rightarrow \lambda \mathbb{E}R.$$

Also, for the current reward $\gamma(t) = \mathbb{E}R_{N_t+1}$ we have

Theorem 4.6. *As $t \rightarrow \infty$*

$$\gamma(t) \rightarrow \lambda \mathbb{E}(R\xi).$$

Remark. The factor ξ comes from size-biasing.

Example. Alternating renewal process: a machine runs and then breaks after time X_i when it takes time Y_i to get fixed ($X_i, Y_i \geq 0$ iid). Thus $\xi_i = X_i + Y_i$ is the length of a full cycle and defines a renewal process (N_t) . What is the fraction of time the machine runs in the long-run? If we let $R_i = X_i$ then have

$$\frac{R(t)}{t} \rightarrow \lambda \mathbb{E}X_1 = \frac{\mathbb{E}X_1}{\mathbb{E}X_1 + \mathbb{E}Y_1} \text{ almost surely.}$$

What is the probability $p(t)$ that the machine is on at time t ? $\mathbb{E}R(t) = \int_0^t P(s)ds$ and we expect (and is true under suitable assumptions that)

$$p(t) \rightarrow \frac{\mathbb{E}X_1}{\mathbb{E}X_1 + \mathbb{E}Y_1}.$$

Remark. $\frac{R(t)}{t}$ is not exactly the same as before, as the reward in reward-renewal processes are only collected at the end of the cycle. But in the long-run this won't change the answer for the limit of $R(t)/t$.

Example. Busy period for M/G/1: assume $\rho < 1$. Let I_n and B_n denote the lengths of the n th idle and busy periods respectively. Then (B_n, I_n) is an alternating reward-renewal process. Hence if $p(t)$ is the probability the server is idle at time t , we have

$$p(t) \xrightarrow{t \rightarrow \infty} \frac{\mathbb{E}I_1}{\mathbb{E}I_1 + \mathbb{E}B_1} = \frac{\frac{1}{\lambda}}{\frac{1}{\lambda} + \frac{1}{\mu - \lambda}} = \frac{\mu - \lambda}{\mu} = 1 - \frac{\lambda}{\mu}.$$

Since $I_n \sim \text{Exp}(\lambda)$ by the Markov property and $\mathbb{E}B_1 = \frac{1}{\mu - \lambda}$ by an earlier result. For an M/M/1 queue we would have

$$p(t) \xrightarrow{t \rightarrow \infty} \pi_0 = 1 - \rho$$

.

Example. Optimal replacement strategy: a car has a random life time $V \geq 0$. The replacement cost is $C_1 > 0$ if the car has not failed, and $C_1 + C_2 > C_1$ if the car fails (if it fails, pay towing cost C_2 and buying cost C_1 ; if not, gift to a friend and buy a new one at cost C_1). What is the optimal strategy schedule for replacing the car to minimise the long-term running cost?

Model this as a renewal-reward process. Strategy: we buy a new car and then after a fixed time $T > 0$, if it is still running we give it away; if it breaks before time T buy a new one. The renewal are $\xi_i = \min\{V_i, T\}$ and reward $R_i = C_1 + C_2 \mathbb{1}(V_i < T)$. Hence

$$\frac{R(t)}{t} \rightarrow \frac{\mathbb{E}R}{\mathbb{E}\xi} = \frac{C_1 + C_2 \mathbb{P}(V_i < t)}{\int_0^T \bar{F}(t) dt} = \frac{C_1 + C_2 F(T)}{\int_0^T \bar{F}(t) dt}$$

where $F(T) = \mathbb{P}(V \leq T)$ and $\bar{F}(t) = \mathbb{P}(V > t)$. So we choose T which minimises $g(T) = \frac{C_1 + C_2 F(T)}{\int_0^T \bar{F}(t) dt}$.

For example if $V \sim U(0, 2)$, then for $T \leq 2$,

$$g(T) = \frac{C_1 + \frac{C_2 T}{2}}{\int_0^T \left(\frac{2-x}{2}\right) dx} = \frac{4C_1 + 2C_2 T}{4T - T^2}$$

which is minimised at $T^* = 2 \left(\sqrt{\left(\frac{C_1}{C_2}\right)^2 + 2\frac{C_1}{C_2}} - \frac{C_1}{C_2} \right) < 2$.

Example. Train dispatch problem: suppose that passengers arrive at a platform according to a renewal process at rate μ (i.e. some iid distribution $(\xi_i)_{i \geq 1}$ of mean $1/\mu$). As soon as N passengers arrive, a train departs immediately with all N on board and the process continues.

The company that runs the train incurs a cost at the rate of $nc > 0$ per unit of time when exactly n passengers are waiting, and a fixed cost K each time a train departs.

What is the optimal value for N ? (Exercise.)

Little's Formula

Definition. A process $(X_t)_{t \geq 0}$ is *regenerative* if there exist random times τ_n such that the process regenerates after time τ_n , i.e.

$$(X_{t+\tau_n})_{t \geq 0} \stackrel{d}{=} (X_t)_{t \geq 0} \text{ and } (X_{t+\tau_n})_{t \geq 0} \text{ is independent of } (X_t)_{t \leq \tau_n}.$$

Also $\tau_0 = 0$, $\tau_n < \tau_{n+1}$ and τ_n depends only on $(X_{t+\tau_n})_{t \geq 0}$ (so $(\tau_{n+1} - \tau_n)$ are iid).

Example. An M/G/1 queue is regenerative with τ_n the end of the n th busy period.

Theorem 4.7 (Little's formula). *Let X be a queue starting from 0 that is regenerative with regeneration times (τ_n) . Let N be the arrival process of X and let W_i be the waiting time of the i th customer (including the service time). Assume $\mathbb{E}\tau_1 < \infty$ and $\mathbb{E}N_{\tau_1} < \infty$. Then almost surely the following limits exist and are deterministic*

- (a) Long-running queue size: $L = \lim_{t \rightarrow \infty} \frac{1}{t} \int_0^t X_s ds$;
- (b) Long-run average waiting time: $W = \lim_{n \rightarrow \infty} \frac{W_1 + \dots + W_n}{n}$;
- (c) Long-run average arrival rate: $\lambda = \lim_{t \rightarrow \infty} \frac{N_t}{t}$.

Furthermore, $L = \lambda W$. In fact, $L = \lambda W$ holds only assuming (b) and (c) and that $X_t/t \rightarrow 0$.

Remark. This theorem is surprisingly general and simple - and so is its proof. No assumption is made on the arrival distribution, the waiting time distribution, the number of servers, or the order in which they are served.

Proof. Set $Y_n = \sum_{i=1}^{N_{\tau_n}} W_i$. Since $X_0 = 0$, by the regeneration property, $X_{\tau_n} = 0$. Let $\tau_n \leq t < \tau_{n+1}$, then since $\int_0^{\tau_n} X_s ds = \sum_{i=1}^{N_{\tau_n}} W_i$ we have

$$\frac{1}{\tau_{n+1}} Y_n \leq \frac{1}{t} \int_0^t X_s ds \leq \frac{1}{\tau_n} Y_{n+1}. \quad (*)$$

By the regeneration property, $Y_i - Y_{i-1}$ are iid. Also $Y_0 = 0$ and $\mathbb{E}\tau_1 < \infty$, so by the Strong Law of Large Numbers

$$\begin{aligned} \frac{Y_n}{\tau_n} &= \frac{(Y_n - Y_{n-1}) + (Y_{n-1} - Y_{n-2}) + \dots + Y_1}{n} \times \frac{n}{(\tau_n - \tau_{n-1}) + \dots + \tau_1} \\ &\rightarrow \frac{\mathbb{E}Y_1}{\mathbb{E}\tau_1} := L \text{ almost surely.} \end{aligned}$$

Hence by (*), $\frac{1}{t} \int_0^t X_s ds \rightarrow L$ almost surely. Similarly,

$$\frac{N_{\tau_n}}{\tau_{n+1}} \leq \frac{N_t}{t} \leq \frac{N_{\tau_{n+1}}}{\tau_n}$$

and $N_{\tau_n} = \sum_{i=0}^{n-1} N_{(\tau_i, \tau_{i+1}]}$. So by the SLLN again, $\frac{N_t}{t} \rightarrow \lambda$ almost surely where $\lambda = \mathbb{E}\tau_1 < \infty$.

Also for $N_{\tau_n} \leq k < N_{\tau_{n+1}}$ have

$$\frac{Y_n}{N_{\tau_{n+1}}} = \frac{1}{k} \sum_{i=1}^k W_i \leq \frac{Y_{n+1}}{N_{\tau_n}}$$

and $\frac{Y_n}{N_{\tau_{n+1}}} = \frac{Y_n}{\tau_{n+1}} \frac{\tau_{n+1}}{N_{\tau_{n+1}}} \rightarrow \frac{L}{\lambda}$ almost surely by the SLLN.

For the second part (noting $N_t - X_t = \# \text{customers that have completed service}$),

$$\sum_{i=1}^{N_t - X_t} W_i \leq \int_0^t X_s ds \leq \sum_{i=1}^{N_t} W_i.$$

Since $\frac{N_t}{t} \rightarrow \lambda > 0$ almost surely and $\frac{X_t}{t} \rightarrow 0$, have $\frac{N_t - X_t}{t} \rightarrow \lambda$ almost surely, so

$$\frac{\int_0^t X_s ds}{t} \rightarrow W\lambda.$$

□

5 Spatial Poisson Process

The standard Poisson process on \mathbb{R}^+ can be encoded by the set of arrival times $0 < T_1 < T_2 < \dots$, so let $\Pi = \{T_1, T_2, \dots\}$. Then Π is a countable random subset of $[0, \infty)$.

The *spatial Poisson process* is a random countable subset Π of \mathbb{R}^d , $d \geq 1$ (with certain processes).