

## Introduction

Schedule:

- (I) Basic properties of continuous-time Markov Chains
- (II) Qualitative properties of continuous time Markov Chains
- (III) Queueing theory
- (IV) Renewal theory
- (V) Spatial Poisson processes

## 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  $\mu$ , 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  $\omega, t$ ) 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’  $\zeta$ , 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  $X_\infty$  is not defined. The explosion time  $\zeta$  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 ‘ $\infty$ ’). 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  $\lambda$ . 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  $\lambda$ . Then for all  $s \geq 0$ , the process  $(X_{s+t} - X_s)_{t \geq 0}$  is also a Poisson process of intensity  $\lambda$ , 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  $\lambda$  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  $\lambda$ . 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  $\lambda$  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  $\lambda$  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  $\lambda$ )
- (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  $\lambda$  and  $\mu$  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  $\lambda$ . 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  $\lambda p$  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  $\lambda p$ . 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  $\lambda$ . 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  $\lambda$  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  $\lambda$  a probability measure on the state space  $I$ . Then a (minimal) random process  $X$  is a *Markov process* with initial distribution  $\lambda$  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( $\lambda, Q$ ) 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( $\lambda, Q$ ) 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( $\lambda, Q$ ) 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( $\delta_x, Q$ ) 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  $Q = \left. \frac{d}{dt} \right|_{t=0} P(t)$ , we have

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

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  $Y$ ,  $\pi$  is an *invariant measure* for  $Y$  if  $\pi P = \pi$ . If in addition  $\sum \pi_i = 1$ ,  $\pi$  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,  $\lambda$  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  $\lambda$  be a measure. Then  $\lambda$  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.  $\pi$  is invariant for  $X$  if and only if  $\mu$  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  $\nu^x$  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  $\lambda$  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,  $\nu^x$  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  $\mu_x$  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  $\beta$  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  $\lambda$  be a measure. Then  $\lambda Q = 0$  if and only if  $\lambda P(s) = \lambda$  for all  $s > 0$ .*

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

Any measure  $\lambda$  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  $\lambda$  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  $\nu^x$  is an invariant measure for  $Y$ . So  $\mu^x$  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

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

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  $\lambda$  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  $\lambda$  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  $\mathcal{E}$   $\pi$  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  $\pi$ . 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  $\pi$  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  $\pi$  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  $\pi$ , 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  $\lambda$  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  $\lambda$  are in detailed balance, then  $\lambda$  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  $\pi$  a distribution with  $X_0 \sim \pi$ . Then  $\pi$  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  $\pi$  is an invariant distribution, where  $\hat{q}_{xy} = \frac{\pi(y)}{\pi(x)} q_{yx}$ . This happens iff  $\pi$  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  $\pi$  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  $\pi$  is invariant it satisfies the detailed balance equation. Indeed, let  $\pi$  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  $\lambda$ . 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  $\infty$ ).

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/ $\infty$  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.  $\pi(n+1) = \pi(0)(\lambda/\mu)^{n+1}$ . So  $\pi$  is normalisable iff  $\lambda/\mu = \rho < 1$ . When  $\rho < 1$ ,  $\pi(n) = (1 - \rho)\rho^n$  is an invariant distribution. So  $\pi$  is the distribution of a (shifted) geometric random variable, i.e.  $\pi$  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,  $\pi$  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/ $\infty$ :

**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  $\mu$  is an invariant measure for  $Y$ . It is enough to check that  $\mu$  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  $\lambda$ .

**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  $\lambda$ , then for any  $T > 0$ ,  $\hat{N}_t = N_T - N_{T-t}$  is again a Poisson Process of rate  $\lambda$  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/ $\infty$  queue with  $\mu, \lambda > 0$ . At equilibrium (i.e  $X_0 \sim \pi$ ),  $D$  is a Poisson process of rate  $\lambda$  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,  $\pi$  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  $(\hat{X}_t)_{0 \leq t \leq T} =^d (X_t)_{0 \leq t \leq T}$ . Hence the arrival process  $\hat{A}$  for  $\hat{X}$  (until time  $T$ ) is a Poisson Process of rate  $\lambda$ . 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  $\lambda$  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  $\lambda$  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  $\lambda$  and  $\mu_1$ . After a customer is served, they immediately join a second M/M/1 queue with parameters  $\lambda$  and  $\mu_2$ . 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  $\lambda$ , which is the arrival process for the second queue.

So the second queue is M/M/1( $\lambda, \mu_2$ ) 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  $\pi$  is invariant for  $(X, Y)$  (by the following exercise).  $\square$

**Exercise:** if  $Z$  is irreducible,  $\pi$  a distribution and  $\pi P(t) = \pi$  for all  $t$ , then  $\pi$  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  $\lambda_k$  and service rates  $\mu_k$ ,  $1 \leq k \leq N$ . 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  $\lambda$  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  $\pi$  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  $\pi$  satisfies this, then  $\pi$  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  $\lambda$ . Service time of  $n$ th customer:  $\xi_n \geq 0$  and  $(\xi_n)$  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  $\xi_{n+1}$ . Then the  $A_n$  are iid (by the independent increment property of a Poisson process), and given  $\xi_n$ ,  $A_n \sim \text{Poi}(\lambda \xi_n)$ , 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.  $\square$