

# **Stochastics** Methods and Problems

Tyler Chen

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# 1 Random Variables and Distributions

## 1.1 Basic Definitions

### 1.1.1 Probability Mass Function (discrete)

$$p(k) = \mathbb{P}(X = k)$$

### 1.1.2 Probability Density Function (continuous)

$$f(x)dx = \mathbb{P}(X \in [x, x + dx))$$

### 1.1.3 Cumulative Density Function

$$F(x) = \mathbb{P}(X < x) = \begin{cases} \sum_{k=0}^{\lfloor x \rfloor} p(k) & \text{discrete} \\ \int_{-\infty}^x f(x)dx & \text{continuous} \end{cases}$$

Can obtain probability density function by,

$$f(x) = \frac{d}{dx}F(x)$$

### 1.1.4 Probability Generating Function

$$G(z) = \mathbb{E}[z^X] = p(0) + p(1)z + p(2)z^2 + p(3)z^3 + \dots$$

Can obtain probability mass function by,

$$p(k) = \frac{1}{k!} \left[ \frac{d^k}{dz^k} G(z) \right]_{z=0}$$

### 1.1.5 Characteristic Function

$$\phi(t) = \mathbb{E}[e^{itX}]$$

*Note: WHAT DO WE USE THIS FOR??*

## 1.2 Bernoulli

Models if a heads is flipped for a biased coin.

Parameters	$p \in [0, 1]$
Support	$\{0, 1\}$
PMF	$\begin{cases} 1 - p & k = 0 \\ p & k = 1 \end{cases}$
Mean	$p$
Variance	$p(1 - p)$
PGF	$(1 - p) + pz$
CF	$(1 - p) + pe^{it}$

## 1.3 Binomial

Models the number of heads when flipping a biased coin  $n$  times.

Parameters	$p \in [0, 1], n \in \mathbb{N}_{\geq 0}$
Support	$\{0, 1, \dots, n\}$
PMF	$\binom{n}{k} p^k (1 - p)^{n-k}$
Mean	$np$
Variance	$np(1 - p)$
PGF	$[(1 - p) + pz]^n$
CF	$[(1 - p) + pe^{it}]^n$

## 1.4 Geometric

Models the number of flips of a biased coin required to flip a heads.

Parameters	$p \in [0, 1]$
Support	$\{1, \dots, n\}$
PMF	$p(1 - p)^{k-1}$
CDF	$1 - (1 - p)^k$
Mean	$1/p$
Variance	$(1 - p)/p^2$
PGF	$ps/(1 - (1 - p)s)$
CF	$pe^{it}/(1 - (1 - p)e^{it})$

## 1.5 Poisson

Expresses the probability of a given number of events occurring in a fixed interval of time or space if these events occur with a known constant rate and independently of the time since the last event.

Parameters	$\lambda > 0$
Support	$\{0, 1, 2, \dots\}$
PMF	$\lambda^k e^{-\lambda}/k!$
CDF	$e^{-\lambda} \sum_{j=0}^k \lambda^j/j!$
Mean	$\lambda$
Variance	$\lambda$
PGF	$\exp(\lambda(z - 1))$
CF	$\exp(\lambda(e^{it} - 1))$

## 1.6 Exponential

Describes times between events in a Poisson point process.

Parameters	$\lambda > 0$
Support	$[0, \infty)$
PDF	$\lambda e^{-\lambda x}$
CDF	$1 - e^{-\lambda x}$
Mean	$1/\lambda$
Variance	$1/\lambda^2$
CF	$\lambda/(\lambda - it)$



## 2 Table of Random (COUNTING?????) Processes

### 2.1 Poisson Point Process

A process in which events occur continuously and independently at a constant average rate

*Note: IS THIS ENOUGH TO DESCRIBE PPP UNIQUELY?*

#### 2.1.1 Viewed as a Counting Process

A counting process  $N = (N_t)_{t \geq 0}$  is a Poisson process with parameter  $\lambda$  if it has the properties,

1.  $N_0 = 0$
2. independent increments
3. the number of points in any time interval of length  $t$  is a Poisson random variable with parameter  $\lambda t$

In other words, a Poisson point process has probability mass function,

$$\mathbb{P}(N_t = n) = \frac{(\lambda t)^n}{n!} e^{-\lambda t}$$

#### 2.1.2 Memoryless property

The distance between two consecutive points will be an exponential random variable with parameter  $\lambda$  (mean  $1/\lambda$ ).

#### 2.1.3 Probability of Jump

$$\mathbb{P}(N_{t+s} = n + m | N_t = n) = \begin{cases} 1 - \lambda s + \mathcal{O}(s^2) & m = 0 \\ \lambda s + \mathcal{O}(s^2) & m = 1 \\ \mathcal{O}(s^2) & m \geq 2 \end{cases}$$

*Note: Something about exponentially distributed counting process*

### 3 Generating and Characteristic functions

how to get density from gen function

## 4 Discrete Time Markov Chains

### 4.1 Transition Matrix

*Sample Problems:*

- **Exercise 4.1:** Write down transition matrices for processes based on rolling a dice
- **Exercise 4.2:** Write down transition matrices for  $Y_n = X_{2n}$
- **Exercise 4.7:** Give example of transition matrix with multiple stationary distributions

### 4.2 Classification of States

*Sample Problems:*

- **Exercise 4.3:** Show if all states communicate with an absorbing state they must all be transient

### 4.3 Mean Recurrence Time

In general find stationary distribution and invert  $i$ -th entry to find mean recurrence time to state  $i$ . *Sample Problems:*

- **Exercise 4.4:** Find expected visits to a state given some properties
- **Exercise 4.5:** Find mean-recurrence times using invariant distribution

### 4.4 Reversibility

*Sample Problems:*

- **Exercise 4.8:** Show process is reversible in equilibrium

### 4.5 Stationary/Invariant distribution

**Note:** TALK ABOUT VARIOUS METHODS FOR FINDING THIS

*Sample Problems:*

- **Exercise 4.5:** Find invariant distribution
- **Exercise 4.6:** Find invariant distribution of mistakes in editions of a book by computing limit of generating function
- **Exercise 4.7:** Give example of transition matrix with multiple stationary distributions

## 4.6 Generating Functions

*Sample Problems:*

- **Exercise 4.6:** Find invariant distribution of mistakes in editions of a book by computing limit of generating function

## 5 Continuous Time Markov Chains

### 5.1 Transition Matrix

### 5.2 Stationary/Invariant distribution

*Methods to find Invariant Distribution:*

- Solve  $\pi P = \pi$
- Solve  $\pi G = 0$
- Find  $G_{X_t}(z)$  and take limit as  $z \rightarrow \infty$

*Sample Problems:*

- **Exercise 5.1:** Find invariant distribution and conditions for existence
- **Exercise 5.2:** Show two processes have the same stationary distribution
- **Exercise 5.3:** Indirectly find stationary distribution by solving KFE, finding generating function for the chain, and computing the distribution of  $X_t$  as  $t \rightarrow \infty$

### 5.3 Generator

*Sample Problems:*

- **Exercise 5.1:** Write down generator
- **Exercise 5.3:** Given generator find Generating function
- **Exercise 5.4:** Write down generator and solve KFE/KBE

### 5.4 KFE AND KBE

Given infinitesimal generator  $G$  we have,

$$\begin{array}{ll} \text{KFE :} & \frac{d}{dt} P_t = P_t G \\ \text{KBE :} & \frac{d}{dt} P_t = G P_t \end{array}$$

### 5.5 Generating Functions

We can use the KFE and KBE to find the generating function of  $X_t$ .

From definition,

$$G_{X_t}(z) = \mathbb{E}[z^{X_t} | X_0 = i] = \sum_{j=0}^{\infty} z^j p_t(i, j)$$

It then follows that,

$$\frac{\partial}{\partial t} G_{X_t}(z) = \sum_{j=0}^{\infty} s^j \frac{\partial}{\partial t} p_t(i, j), \quad \frac{\partial}{\partial z} G_{X_t}(z) = \sum_{j=1}^{\infty} j s^{j-1} p_t(i, j)$$

## 5.6 Computing Generating Functions

1. Write down KFE or KBE equations
2. Add equations together and PDE involving  $G_{X_t}(z)$ ,  $\partial_t G_{X_t}(z)$ , and  $\partial_z G_{X_t}(z)$
3. Use initial condition  $G_{X_t}(z) = z^i$  ( $X_0 = i$ ) to solve PDE

*Sample Problems:*

- **Exercise 5.3:** Use KBE to find PDE for generating function of  $X$
- **Exercise 5.4:** Use KBE to find PDE for generating function of  $X$
- **Exercise 5.5:** Compute generating function of Poisson process with random intensity. Use generating function to compute mean and variance.

## 5.7 Finding PDEs

*Sample Problems:*

- **Exercise 5.3:** Given generator solve KFE
- **Exercise 5.4:** Write down KFE and KBE and solve

### 5.7.1 note OTHER METHODS?

## 5.8 Birth Death Processes

General description of birth death processes

### 5.8.1 General Form for infinite queue

*Description:*

- Process either jumps up one or down one or stay the same
- Expected wait time in state  $i$  is exponentially distributed  $\tau \sim \mathcal{E}(\lambda_i + \mu_i)$
- When the process does jump, the probability of an up jump is  $\lambda_i/(\lambda_i + \mu_i)$ , and the probability of a down jump is  $\mu_i/(\lambda_i + \mu_i)$ .
- if  $\lambda_0 > 0$  the chain is irreducible.

*State space:*  $S = \{1, 2, 3, \dots\}$ .

*Generator:*

$$G = \begin{bmatrix} -\lambda_0 & \lambda_0 & & & \\ \mu_1 & -(\mu_1 + \lambda_1) & \lambda_1 & & \\ & \mu_2 & -(\mu_2 + \lambda_2) & \lambda_2 & \\ & & \mu_3 & -(\mu_3 + \lambda_3) & \lambda_3 \\ & & & & \ddots \end{bmatrix}$$

*Invariant distribution:*

$$\pi(k) = \frac{\lambda_0 \lambda_1 \cdots \lambda_{k-1}}{\mu_1 \mu_2 \cdots \mu_k} \pi(0), \quad \pi(0) = \left( 1 + \sum_{k=1}^{\infty} \frac{\lambda_0 \lambda_1 \cdots \lambda_{k-1}}{\mu_1 \mu_2 \cdots \mu_k} \right)^{-1}$$

*Sample Problems:* Example 5.2.9

### 5.8.2 M/M/1 queue

*Description:*

- Models infinite queue.
- Arrivals occur at a rate  $\lambda$  according to a Poisson process.
- Service times have exponential distribution with rate parameter  $\mu$ , where  $1/\mu$  is the mean service time.
- A single server serves customers one at a time from front of queue, first come first serve

*State space:*  $S = \{1, 2, 3, \dots\}$ .

*Generator:*

$$G = \begin{bmatrix} -\lambda & \lambda & & \\ \mu & -(\mu + \lambda) & \lambda & \\ & \mu & -(\mu + \lambda) & \lambda \\ & & & \ddots \end{bmatrix}$$

*Invariant distribution:*

$$\pi(k) = (1 - \lambda/\mu)(\lambda/\mu)^k$$

*Expected Response Time:* For customers who arrive and find the queue as a stationary process, the response time (sum of waiting and services times) has density function,

$$f(t) = \begin{cases} (\mu - \lambda)e^{-(\mu - \lambda)t}, & t > 0 \\ 0 & \text{ow.} \end{cases}$$

This has mean,

$$\int_0^{\infty} t f(t) dt = \frac{1}{\mu - \lambda}$$

*Sample Problems:*

- **Exercise 5.1:** fdsaf sad

### 5.8.3 M/M/ $\infty$

*Description:*

- Arrivals occur at a rate  $\lambda$  according to a Poisson process.
- Service times have exponential distribution with rate parameter  $\mu$ , where  $1/\mu$  is the mean service time.
- There are always enough servers that every arriving job is serviced immediately.

*State space:*  $S = \{1, 2, 3, \dots\}$ .

*Generator:*

$$G = \begin{bmatrix} -\lambda & \lambda & & & \\ \mu & -(\mu + \lambda) & \lambda & & \\ & 2\mu & -(2\mu + \lambda) & \lambda & \\ & & 3\mu & -(3\mu + \lambda) & \lambda \\ & & & \ddots & \ddots \end{bmatrix}$$

*Invariant Distribution:*

$$\pi(k) = \frac{(\lambda/\mu)^k e^{-\lambda/\mu}}{k!}$$

*Sample Problems:* **Exercise 5.3**, Final Problem ??, Practice Exam #? Problem 1

### 5.8.4 M/M/1/K queue

*State space:*  $S = \{1, 2, \dots, n\}$ .

*Generator:*

$$G = \begin{bmatrix} -\lambda & \lambda & & & \\ \mu & -(\mu + \lambda) & \lambda & & \\ & \mu & -(\mu + \lambda) & \lambda & \\ & & \ddots & \ddots & \ddots \\ & & & \mu & -(\mu + \lambda) & \lambda \\ & & & & \mu & -\mu \end{bmatrix}$$



## 6 Brownian Motion

*Note:* add examples from class notes

### 6.1 Martingale

*Sample Problems:*

- **Exercise 7.1:** Show a process is a Martingale using definition
- **Exercise 7.4:** Show a process is a Martingale using definition

### 6.2 Characteristic Functions

*Sample Problems:*

- **Exercise 7.2:** Compute characteristic function of  $W(N(t))$ , where  $N \sim \text{Pois}(\lambda)$

7.3: n-th variation time

### 6.3 Laplace Transform

*Sample Problems:*

- *Note:* Example ??? from book
- **Exercise 7.4:** Compute Laplace transform of first hitting time.

## 7 Stochastic Calculus

*Note: ITO FORMULA AND STUFF*

### 7.1 Itô's Formula

*One Dimension:*

$$df(X_t) = f'(X_t)dX_t + \frac{1}{2}f''(X_t)d[X, X]_t$$

*Two Dimensions:*

$$df(t, X_t) = f_t(t, X_t)dt + f_x(t, X_t)dX_t + \frac{1}{2}f_{xx}(t, X_t)d[X, X]_t$$

*Two Dimensions:*

$$\begin{aligned} df(X_t, Y_t) &= f_x(X_t, Y_t)dX_t + f_y(X_t, Y_t)dY_t \\ &+ \frac{1}{2} \left( f_{xx}(X_t, Y_t)d[X, X]_t + f_{xy}(X_t, Y_t)d[X, Y]_t \right. \\ &\quad \left. + f_{yx}(X_t, Y_t)d[Y, X]_t + f_{yy}(X_t, Y_t)d[Y, Y]_t \right) \end{aligned}$$

### 7.2 Product Rule

$$d(X_t Y_t) = Y_t dX_t + X_t dY_t + d[X, Y]_t$$

### 7.3 Girsanov's Theorem

*Sample Problems:*

- Practice Exam 4, Problem 2

## 8 SDEs and PDEs

*Note: unclassified:* Exercise 9.1 Exercise 9.4 Exercise 9.5 Exercise 9.6

Exercise 9.7 (no solution for this)

### 8.1 SDEs

*Sample Problems:*

- **Exercise 9.3:** Use Itô's Lemma to derive SDE for two new processes defined in terms of other processes

#### 8.1.1 Geometric Brownian Motion

#### 8.1.2 Ornstein–Uhlenbeck (OU) process

*SDE:*

$$dX_t = \kappa(\theta - X_t)dt + \sigma dW_t$$

*Solution:*

$$X_t = \theta + e^{-\kappa t}(X_0 - \theta) + \int_0^t e^{-\kappa(t-s)}\sigma dW_s$$

*Transition Density: Note: TODO*

*Note: ALSO ADD DIFFERENT BOUNDARY CONDITIONS*

### 8.2 Infinitesimal Generator

Suppose  $X = (X_t)_{t \geq 0}$  is given by,

$$X_t = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_d \end{bmatrix} dt + \begin{bmatrix} \sigma_{1,1} & \sigma_{1,2} & \cdots & \sigma_{1,d} \\ \sigma_{2,1} & & & \sigma_{2,d} \\ \vdots & & & \vdots \\ \sigma_{d,1} & \sigma_{d,2} & \cdots & \sigma_{d,d} \end{bmatrix} \begin{bmatrix} dW_t^1 \\ dW_t^2 \\ \vdots \\ dW_t^d \end{bmatrix}$$

where  $\mu_i$  and  $\sigma_{ij}$  depend on  $(t, X_t)$ .

The infinitesimal generator of  $X$  is given by,

$$\mathcal{A}(t) = \sum_{i=1}^d \mu_i(t, x) \partial_{x_i} + \frac{1}{2} \sum_{i=1}^d \sum_{j=1}^d (\sigma \sigma^T)_{i,j}(t, X_t) \partial_{x_i} \partial_{x_j}$$

### 8.3 Kolmogorov Backwards Equation

Let  $X = (X_t)_{t \geq 0}$  be the solution of an SDE of the form,

$$dX_t = \mu(t, X_t)dt + \sigma(t, X_t)dW_t$$

where  $\mu : \mathbb{R}_+ \times \mathbb{R} \rightarrow \mathbb{R}^d$  and  $\sigma : \mathbb{R}_+ \times \mathbb{R} \rightarrow \mathbb{R}^{d \times d}$ . For some suitable function  $\varphi$ , define,

$$u(t, X_t) := \mathbb{E}[\varphi(X_T) | \mathcal{F}_t]$$

If  $u \in C^{1,2}$  then it satisfies the Kolmogorov Backward Equation,

$$(\partial_t + \mathcal{A}(t))u(t, \cdot) = 0, \quad u(T, \cdot) = \varphi$$

#### 8.3.1 Speed and Scale Densities

In one dimension, a time homogeneous process  $dX_t = \mu(X_t)dt + \sigma(X_t)dW_t$  has generator,

$$\mathcal{A}(t) = \mu(x)\partial_x + \frac{1}{2}\sigma^2(x)\partial_x^2$$

We can write this as,

$$\mathcal{A} = \frac{1}{m(x)}\partial_x \left( \frac{1}{s(x)}\partial_x \right)$$

where  $s(x)$  and  $m(x)$  are respectively called the scale and speed densities, and are given by,

$$s(x) = \exp \left( -2 \int \frac{\mu(x)}{\sigma^2(x)} dx \right), \quad m(x) = \frac{2}{\sigma^2(x)} \exp \left( 2 \int \frac{\mu(x)}{\sigma^2(x)} dx \right)$$

If  $m$  is normalizable then  $m$  is a time-homogeneous solution to the KFE and a stationary density for  $X$ .

#### 8.3.2 Computing Solution to KBE for 1d Time Homogeneous Process

1. Write down infinitesimal generator  $\mathcal{A}$
2. Write down speed density  $m(x)$
3. Find complete set of eigenfunctions,  $\{\psi_n\}$  of  $\mathcal{A}$  satisfying,  $\mathcal{A}\psi_n = \lambda_n\psi_n$
4. Normalize eigenvectors wrt.  $m$  so that  $\langle \psi_n, \psi_n \rangle_m = 1$ .
5. Compute,

$$u(t, x) = \sum_n e^{(T-t)\lambda_n} \langle \psi_n, \varphi \rangle_m \psi_n$$

## 8.4 Transition Density

The transition density is defined as,

$$\Gamma(t, x; T, y) = \mathbb{P}(X_T \in dy | X_t = x)$$

and satisfies,

$$\begin{aligned} \text{KBE :} \quad & (\partial_t + \mathcal{A}(t))\Gamma(t, \cdot; T, y) = 0, & \Gamma(T, \cdot; T, y) &= \delta_y \\ \text{KFE :} \quad & (-\partial_T + \mathcal{A}^*(T))\Gamma(t, x; T, \cdot) = 0, & \Gamma(T, x; T, \cdot) &= \delta_x \end{aligned}$$

### 8.4.1 Boundary Conditions

$$\begin{aligned} \text{killing :} & \quad [f(x)]_{\text{on } \partial R} = 0 \\ \text{reflecting :} & \quad \left[ \frac{1}{s(x)} \partial_x f(x) \right]_{\text{on } \partial R} = 0 \\ \text{natural :} & \quad \text{no boundary conditions} \end{aligned}$$

### 8.4.2 Computing Transition Density

1. Write down infinitesimal generator  $\mathcal{A}$
2. Write down speed density  $m(x)$  and scale density  $s(x)$
3. Write down boundary conditions
4. Find complete set of eigenfunctions,  $\{\psi_n\}$  of  $\mathcal{A}$  satisfying,  $\mathcal{A}\psi_n = \lambda_n\psi_n$  and boundary conditions.
5. Normalize eigenvectors wrt.  $m$  so that  $\langle \psi_n, \psi_n \rangle_m = 1$ .
6. Compute,

$$\Gamma(t, x; T, y) = m(y) \sum_n e^{(T-t)\lambda_n} \psi_n(y) \psi_n(x)$$

*Sample Problems:*

- **Practice Exam 3, Problem 2:** Find transition density for constant coefficient process with reflecting boundary conditions.
- **Practice Exam 5, Problem 2:** Find transition density for mean repelling OU process (two different approaches)

## 8.5 Finding PDEs Using Martingale Process

1. Find a martingale process depending on  $u(t, X_t)$ .
2. Take the differential of it.
3. Set the  $dt$  term to zero.

This will give a PDE which  $u(t, X_t)$  satisfies.

*Sample Problems:*

- Theorem 9.2.1: Derive KBE
- Theorem 9.2.2: Derive PDE for process,

$$u(t, X_t) = \mathbb{E} \left[ e^{-A(t,T)} \varphi(X_T) + \int_t^T e^{-A(t,s)} g(s, X_s) | \mathcal{F}_t \right], \quad A(t, s) = \int_t^s \gamma(u, X_u) du$$

- **Exercise 9.2:** Find PDE for given expression (solutions given using theorem and by finding martingale)

## 8.6 Finding PDEs for Hitting Time Problems

Given a process  $X = (X_t)_{t \geq 0}$  and some region  $R$ , define,

$$\tau = \inf\{t \geq 0 : X_t \notin R\}$$

Define,

$$u(x) = \mathbb{E} \left[ e^{-\lambda(\tau-t)} \varphi(X_\tau) + \int_t^\tau e^{-\lambda(s-t)} g(X_s) ds \middle| X_t = x \right], \quad t \leq \tau$$

Assuming  $\mathbb{P}(\tau < \infty) = 1$ , the function  $u$  satisfies,

$$(\mathcal{A} - \lambda)u = 0, \quad u = \varphi \text{ on } \partial R$$

where  $\mathcal{A}$  is the **infinitesimal generator** of  $X$ .

*Sample Problems:*

- Theorem 9.4.1: This is that theorem
- Corollary 9.4.2: Find Laplace transform of  $\tau$
- Example 9.4.3: First hitting time of Brownian motion
- **Practice Exam 1, Problem 2:** Find PDE for hitting time of 2d process.

**Note:** ADD ASSOCIATED PDEs

## 9 Jump Diffusions

## 10 Practice Qualification Exams



**Practice Exam 1, Problem 1**

Let  $X = (X_n)_{n \in \mathbb{N}_0}$  be a discrete time Markov chain with  $X_n$  representing the amount of water in a reservoir at noon on day  $n$ . Assume  $X_0 \in \mathbb{N}_0$ . Let  $Y = (Y_n)_{n \in \mathbb{N}_0}$  be a sequence of iid random variables with  $Y_n$  representing the amount of water that flows into the reservoir during the  $n$ -th day. The state space of  $Y$  is  $\{0, 1, 2, \dots\}$ . The reservoir has a maximum capacity of  $K \in \mathbb{N}$ . When the reservoir is filled to level  $K$ , all excessive inflows are lost.

- Write the one-step transition matrix  $P$  of  $X$  in terms of the probability generating function  $G_Y$  of  $Y$ .
- Find an expression for the stationary distribution  $\pi$  of  $X$  in terms of the probability generating function  $G_Y$  of  $Y$ .

**Solution**

- We assume all the water comes in the afternoon. That is,  $X_{n+1} = X_n + Y_n$ .

Suppose on day  $n$  the reservoir is not full. That is,  $X_n = k < K$ . If it is not filled completely by the incoming water, then some amount of water  $j < K - k$  was added. In this case  $X_{n+1} = k + j$  with probability,

$$\mathbb{P}(Y_n = j) = f_Y(j) = \left[ \frac{1}{j!} \frac{d^j G_Y(s)}{ds^j} \right]_{s=0}$$

Otherwise,  $X_{n+1} = K$  with probability,

$$1 - \sum_{j < K-k} f_Y(j) = 1 - \sum_{j < K-k} \left[ \frac{1}{j!} \frac{d^j G_Y(s)}{ds^j} \right]_{s=0}$$

Suppose  $X_n = K$ . Then since no water leaves the reservoir,  $X_{n+1} = K$  with probability one.

We can write this as,

$$X_{n+1} = \begin{cases} 0 & j < i \\ \left[ \frac{1}{j!} \frac{d^j G_Y(s)}{ds^j} \right]_{s=0} & j < K - X_n \\ 1 - \sum_{j < K-X_n} \left[ \frac{1}{j!} \frac{d^j G_Y(s)}{ds^j} \right]_{s=0} & \text{otherwise} \end{cases}$$

Conditioning on  $X_n = i$  we then have,

$$P_{i,j} = \mathbb{P}(X_{n+1} = j | X_n = i) = \begin{cases} 0 & j < i \\ \left[ \frac{1}{j!} \frac{d^j G_Y(s)}{ds^j} \right]_{s=0} & j < K - i \\ 1 - \sum_{j < i} \left[ \frac{1}{j!} \frac{d^j G_Y(s)}{ds^j} \right]_{s=0} & \text{otherwise} \end{cases}$$

(b) Note that  $\pi = [0, 0, \dots, 0, 1]$  is a stationary distribution.

*Note:* argue the distribution is unique?

*Note:* alternative approach?? Clearly  $X_n \rightarrow K$  as  $n \rightarrow \infty$ .

*Note:* in what sense?

**Practice Exam 1, Problem 2**

Let  $(X, Y) = (X_t, Y_t)_{t \geq 0}$  satisfy the following SDE,

$$dX_t = dW_t^1, \quad dY_t = dW_t^2, \quad (X_0, Y_0) = (x, y)$$

where  $W = (W_t^1, W_t^2)_{t \geq 0}$  is a two-dimensional Brownian motion with independent components. Define a process  $(R, \Phi) = (R_t, \Phi_t)_{t \geq 0}$  as follows,

$$\Phi_t = \arctan(Y_t/X_t), \quad R_t^2 = X_t^2 + Y_t^2$$

- (a) Derive the SDEs satisfied by  $(R, \Phi)$ .
- (b) Define,

$$u(r, \phi) = \mathbb{E} \left[ e^{-\lambda \tau} f(R_\tau) | R_0 = r, \Phi_0 = \phi \right], \quad \tau = \inf\{t \geq 0 : \Phi_t \notin (0, \pi/2)\}, \quad \phi \in (0, \pi/2)$$

Derive a PDE satisfied by  $u$ .

- (c) Describe with pseudo-code how you would find  $u(r, \phi)$  using Monte Carlo simulation.

**Solution**

- (a) Define  $f(x, y) = \arctan(y/x)$  and  $g(x, y) = \sqrt{x^2 + y^2}$ . Now note that,

$$\Phi_t = f(X_t, Y_t), \quad R_t = g(X_t, Y_t)$$

Applying Itô's formula we find,

$$\begin{aligned} d\Phi_t &= f_x(X_t, Y_t)dX_t + f_y(X_t, Y_t)dY_t \\ &\quad + \frac{1}{2}(f_{xx}(X_t, Y_t)d[X, X]_t + f_{xy}(X_t, Y_t)d[X, Y]_t \\ &\quad + f_{yx}(X_t, Y_t)d[Y, X]_t + f_{yy}(X_t, Y_t)d[Y, Y]_t) \end{aligned}$$

Using our Heuristics we have,

$$d[X, X]_t = d[Y, Y]_t = dt, \quad d[X, Y]_t = d[Y, X]_t = 0$$

We compute,

$$\begin{aligned} f_x(x, y) &= -\frac{y}{x^2 + y^2} = -\frac{\sin(\arctan(y/x))}{\sqrt{x^2 + y^2}} \\ f_y(x, y) &= \frac{x}{x^2 + y^2} = \frac{\cos(\arctan(y/x))}{\sqrt{x^2 + y^2}} \\ f_{xx}(x, y) &= \frac{2xy}{(x^2 + y^2)^2} \\ f_{yy}(x, y) &= -\frac{2xy}{(x^2 + y^2)^2} \end{aligned}$$

Therefore, making the substitutions,  $\Phi_t = \arctan(Y_t/X_t)$ , and  $R_t = \sqrt{X_t^2 + Y_t^2}$ ,

$$d\Phi_t = -\frac{\sin(\Phi_t)}{R_t}dW_t^1 + \frac{\cos(\Phi_t)}{R_t}dW_t^2$$

Similarly,

$$\begin{aligned} dR_t &= g_x(X_t, Y_t)dX_t + g_y(X_t, Y_t)dY_t \\ &\quad + \frac{1}{2}(g_{xx}(X_t, Y_t)d[X, X]_t + g_{xy}(X_t, Y_t)d[X, Y]_t \\ &\quad + g_{yx}(X_t, Y_t)d[Y, X]_t + g_{yy}(X_t, Y_t)d[Y, Y]_t) \end{aligned}$$

We compute,

$$\begin{aligned} g_x(x, t) &= \frac{x}{\sqrt{x^2 + y^2}} = \cos(\arctan(y/x)) \\ g_y(x, t) &= \frac{y}{\sqrt{x^2 + y^2}} = \sin(\arctan(y/x)) \\ g_{xx}(x, t) &= \frac{y^2}{(x^2 + y^2)^{3/2}} \\ g_{yy}(x, t) &= \frac{x^2}{(x^2 + y^2)^{3/2}} \end{aligned}$$

Therefore, making the substitutions,  $\Phi_t = \arctan(Y_t/X_t)$ , and  $R_t = \sqrt{X_t^2 + Y_t^2}$ ,

$$dR_t = \cos(\Phi_t)dW_t^1 + \sin(\Phi_t)dW_t^2 + \frac{1}{2R_t}dt$$

(b) We know  $u$  satisfies,

$$(\mathcal{A} - \lambda)u = 0, \quad u(r, 0) = u(r, \pi/2) = f(r)$$

where,

$$\mathcal{A} = \frac{1}{2r} \partial_r + \frac{1}{2} \left( \partial_r + \frac{1}{r^2} \partial_\phi^2 \right)$$

(c) We can compute  $u(r, \phi)$  by simulating trajectories of  $R$  and  $\Phi$ , and observing where they end up. In particular, starting at the point  $(R_0, \Phi_0) = (r, \phi)$ , we run a stochastic integrator (forward Euler for instance) until the process exits. We then compute the value of  $e^{-\lambda\tau} f(R_\tau)$ . Repeating this integration many times will give an estimate at the expected value.

To integrate we must set a time step size  $\Delta t$ . At each step  $dW_t^1$  and  $dW_t^2$  will be normally distributed with mean 0 and variance  $\Delta t$ . To advance the solution we generate random normal variables with this mean and variance, and then compute the change using our SDEs for  $R$  and  $\Phi$ , replacing  $dt$  with  $\Delta t$  and  $dW_t^1, dW_t^2$  with the random normal variables. This is repeated iteratively.

**Practice Exam 2, Problem 1**

Let  $Y = (Y_n)_{n \in \mathbb{N}_0}$  be a sequence of iid random variables with  $Y_n \sim \text{Pois}(\lambda)$  representing the number of particles entering a chamber at time  $n$ . The lifetimes of the particles are iid geometric random variables with parameter  $p$ . Let  $X_n$  represent the number of particles in the chamber at time  $n$ .

- (a) Give an expression for  $p(i, j) = \mathbb{P}(X_{n+1} = j | X_n = i)$ .
- (b) Find the stationary distribution  $\pi$  of  $X = (X_n)_{n \geq 0}$ .

**Solution**

- (a) If the lifetime of a particle is a geometric random variable with parameter  $p$ , then at each step there is a probability  $p$  that the particle will decay and a probability  $1 - p$  that the particle will not decay.

Let  $Z_n$  represent the number of particles which *not* decay during the  $n$ -th step. That is,

$$X_{n+1} = Z_n + Y_n$$

Since each of the  $X_n$  particles *not* decay with probability  $1 - p$  we have  $Z_n \sim \text{Bin}(X_n, 1 - p)$  and  $Y_n \sim \text{Pois}(\lambda)$ .

Denote the generating functions of  $Y_n$  and  $Z_n$  by,  $G_{Y_n}(s)$  and  $G_{Z_n}(s)$  respectively. Explicitly,

$$G_{Y_n}(s) = G_Y(s) = e^{\lambda(s-1)}, \quad G_{Z_n}(s) = (p + (1 - p)s)^{X_n} = G_{X_n}(p + (1 - p)s)$$

Assume  $Y_n$  is independent of  $X_n$  and therefore of  $Z_n$ . If  $X_n = i$  the generating function is  $G_{X_n} = s^i$ . We can then write,

$$G_{X_{n+1}}(s) = G_{Y_n}(s)G_{Z_n}(s) = G_Y(s)(p + (1 - p)s)^i = e^{\lambda(s-1)}(p + (1 - p)s)^i$$

Therefore,

$$\begin{aligned} p(i, j) &= \mathbb{P}(X_{n+1} = j | X_n = i) \\ &= \left[ \frac{1}{j!} \frac{d^j G_{X_{n+1}}(s)}{ds^j} \right]_{s=0} \\ &= \left[ \frac{1}{j!} \frac{d^j}{ds^j} \left[ e^{\lambda(s-1)} (p + (1 - p)s)^i \right] \right]_{s=0} \end{aligned}$$

- (b) More generally, the generating function  $G_{X_{n+1}}(s)$  of  $X_{n+1}$  is then,

$$G_{X_{n+1}}(s) = G_{Y_n}(s)G_{Z_n}(s) = G_Y(s)G_{X_n}(p + (1 - p)s)$$

This gives a recurrence relation. We assume  $X_0 = 0$  so that  $G_{X_0}(s) = 1$ . For convenience write  $q = 1 - p$ . Then,

$$1 + q^k(s-1)|_{s=(1+q(s-1))} = 1 + q^k((1 + q(s-1)) - 1) = 1 + q^{k+1}(s-1)$$

Therefore,

$$\begin{aligned} G_{X_n}(s) &= G_Y(s)G_{X_{n-1}}(1 + q(s-1)) \\ &= G_Y(s)G_Y(1 + q(s-1))G_{X_{n-2}}(1 + q^2(s-1)) \\ &\vdots \\ &= \prod_{k=0}^n G_Y(1 + q^k(s-1)) \end{aligned}$$

We can rewrite this as,

$$G_{X_n}(s) = \exp \left( \sum_{k=0}^n \lambda((1 + q^k(s-1)) - 1) \right) = \exp \left( \lambda(s-1) \sum_{k=0}^n q^k \right)$$

Taking the limit as  $n \rightarrow \infty$  we find,

$$\begin{aligned} G_{X_\infty}(s) &= \lim_{n \rightarrow \infty} G_{X_n}(s) \\ &= \exp \left( \lambda(s-1) \sum_{k=0}^{\infty} q^k \right) \\ &= \exp \left( \frac{\lambda(s-1)}{1-q} \right) \\ &= \exp \left( \frac{\lambda}{p}(s-1) \right) \end{aligned}$$

Therefore, by the continuity theorem,  $X_\infty$  is distributed like a Poisson random variable with parameter  $\lambda/p$ .

This means the invariant distribution of  $X$  is the density function of a Poisson random variable with parameter  $\lambda/p$ . That is,

$$\pi(k) = \left( \frac{\lambda}{p} \right)^k \frac{e^{-\lambda/p}}{k!}$$

**Practice Exam 2, Problem 2**

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and a filtration  $\mathbb{F} = (\mathcal{F}_t)_{0 \leq t \leq T}$  where  $T < \infty$ . Consider a process  $P = (P_t)_{0 \leq t \leq T}$  defined as,

$$P_t = \mathbb{E}[\mathbb{1}_{X_T \leq a} | \mathcal{F}_t], \quad dX_t = dW_t$$

where  $W$  is a  $(\mathbb{P}, \mathbb{F})$ -Brownian motion. Derive an SDE for the process  $P$ . Your answer should not involve  $X$ . You may find it useful to use the CDF  $\Phi$  of a standard normal random variable,

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^z e^{-x^2/2} dx$$

its inverse  $\Phi^{-1}$  and its derivative  $\phi := \Phi'$ .

**Solution**

Note that condition on  $\mathcal{F}_t$  is the same as conditioning on  $X_t$ . For notational convenience let  $x = X_t$ . Then,

$$P_t = \mathbb{E}[\mathbb{1}_{X_T \leq a} | \mathcal{F}_t] = \mathbb{P}(X_T \leq a | X_t = x) = \int_{-\infty}^a \Gamma(t, x; T; y) dy$$

Note further that,

$$\Gamma(t, x; T, y) = \frac{1}{\sqrt{2\pi(T-t)}} \exp\left(-\frac{(y-x)^2}{2(T-t)}\right) = \frac{1}{\sqrt{T-t}} \phi\left(\frac{y-x}{\sqrt{T-t}}\right)$$

Let  $u = (y-x)/\sqrt{T-t}$ . Then  $dy = \sqrt{T-t} du$  so,

$$P_t = \int_{-\infty}^a \frac{1}{\sqrt{T-t}} \phi\left(\frac{y-x}{\sqrt{T-t}}\right) dy = \int_{-\infty}^{\frac{a-x}{\sqrt{T-t}}} \phi(u) du = \Phi\left(\frac{a-x}{\sqrt{T-t}}\right)$$

Recall that  $X_t = x$  so,

$$P_t = \Phi\left(\frac{a-X_t}{\sqrt{T-t}}\right)$$

Let  $Y_t = (a-X_t)/\sqrt{T-t} = \Phi^{-1}(P_t)$ . Then,

$$dY_t = \frac{1}{2(T-t)} \frac{a-X_t}{\sqrt{T-t}} dt - \frac{1}{\sqrt{T-t}} dX_t = \frac{Y_t}{2(T-t)} dt - \frac{1}{\sqrt{T-t}} dW_t$$



Therefore,

$$\begin{aligned}
 dP_t &= d\Phi(Y_t) = \phi(Y_t)dY_t + \frac{1}{2}\phi'(Y_t)d[Y, Y]_t \\
 &= \phi(Y_t)\frac{Y_t}{2(T-t)}dt - \phi(Y_t)\frac{1}{\sqrt{T-t}}dW_t + \frac{1}{2}\phi'(Y_t)\frac{1}{T-t}dt \\
 &= \left(\phi(Y_t)\frac{Y_t}{2(T-t)} + \frac{1}{2}\phi'(Y_t)\frac{1}{T-t}\right)dt - \frac{\phi(Y_t)}{\sqrt{T-t}}dW_t
 \end{aligned}$$

We know that  $\phi'(z) = z\phi(z)$ . (alternative argument: As  $P_t$  is a martingale we know the  $dt$  term is zero.) Therefore,

$$dP_t = -\frac{\phi(\Phi^{-1}(P_t))}{\sqrt{T-t}}dW_t$$

**Practice Exam 3, Problem 1**

Let  $X = (X_t)_{t \geq 0}$  be a continuous time Markov chain with  $X_t$  representing the number of individuals in a population at time  $t$ . Individuals do not reproduce. However, immigrants join the population as a Poisson process with parameter  $\lambda$ . The lifetimes of individuals are iid exponentially distributed random variables with parameter  $\mu$ .

- (a) Write the generator  $G$  of  $X$
- (b) Find the stationary distribution  $\pi$  of  $X$ .

**Solution**

- (a) This is a M/M/ $\infty$  queue with arrival parameter  $\lambda$  and service parameter  $\mu$ .

In a short time  $s$  the probability of no immigrant joining the population is  $1 - \lambda s + \mathcal{O}(s^2)$ , the probability of one immigrant joining is  $\lambda s + \mathcal{O}(s^2)$ , and the probability more than one immigrant joining is  $\mathcal{O}(s^2)$ .

Similarly, the probability of a given individual dying is  $\mu s + \mathcal{O}(s^2)$  and the probability of an individual not dying is  $1 - \mu s + \mathcal{O}(s^2)$ .

The generator is then,

$$G = \begin{bmatrix} -\lambda & \lambda & & & & \\ \mu & -(\mu + \lambda) & \lambda & & & \\ & 2\mu & -(2\mu + \lambda) & \lambda & & \\ & & 3\mu & -(3\mu + \lambda) & \lambda & \\ & & & \ddots & \ddots & \ddots \end{bmatrix}$$

- (b) An M/M/ $\infty$  queue with these parameters has invariant distribution,

$$\pi(k) = \frac{(\lambda/\mu)^k e^{-\lambda/\mu}}{k!}$$

**Practice Exam 3, Problem 2**

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and a filtration  $\mathbb{F} = (\mathcal{F}_t)_{t \geq 0}$ . Consider a process  $X = (X_t)_{t \geq 0}$  that satisfies the following SDE,

$$dX_t = bdt + adW_t$$

where  $W$  is a  $(\mathbb{P}, \mathbb{F})$ -Brownian motion. Suppose that  $X_0 \in (L, R)$  and that  $\{L\}$  and  $\{R\}$  are reflecting boundaries.

- (a) Derive an expression for the invariant distribution of  $X$ .
- (b) Derive an expression for the transition density  $\Gamma(t, x; T, y)dy := \mathbb{P}(X_t \in dy | X_t = x)$ .
- (c) Show that  $\Gamma(t, x; T, y) \rightarrow \pi(y)$  as  $T \rightarrow \infty$ .

**Solution**

- (a) We have scale and speed densities,

$$s(x) = \exp \left( -2 \int_L^R \frac{b}{a^2} dx \right) = \exp \left( -2 \frac{b}{a^2} (R - L) \right)$$

$$m(x) = \frac{1}{a^2} \exp \left( 2 \int_L^R \frac{b}{\sigma^2(x)} dx \right) = \frac{1}{a^2} \exp \left( 2 \frac{b}{a^2} (R - L) \right)$$

Since  $m(x)$  is constant on a finite interval it can be normalized (for  $a \neq 0$ ) as  $m(x) = 1/(R - L)$ , which is therefore the invariant distribution of  $X$ .

This makes sense since as time evolves, the Brownian motion term will dominate, and the reflecting boundary condition means that the process becomes constant.

- (b) We have infinitesimal generator,

$$\mathcal{A}(t) = b\partial_x + \frac{1}{2}a^2\partial_x^2$$

The boundary conditions require  $\mathcal{A}$  act on functions satisfying,

$$\left[ \frac{1}{s(x)} \partial_x f(x) \right]_{x \in \{L, R\}} = 0$$

*Note: I don't quite understand this*

We seek a complete set of eigenfunctions  $\{\psi_n(x)\}_{n=0}^\infty$  with corresponding eigenvalues  $\lambda_n$  of  $\mathcal{A}$  satisfying this boundary condition and normalized with respect to  $m$ .

In this case,

$$\Gamma(t, x; T, y) = m(y) \sum_{n=0}^{\infty} e^{(T-t)\lambda_n} \psi_n(y) \psi_n(x)$$

We now find such functions:

*Note: I have no idea*

(c) *Note: Presumably this is easy if you can do (b)*

**Practice Exam 4, Problem 1**

A transition probability matrix  $P$  for a Markov chain with  $N$  states is said to be doubly stochastic if the entries in each of its columns add up to one.

- Show that the uniform distribution given by  $q_i = 1/N$  for all  $j$  is a stationary distribution for such a Markov chain.
- Consider the following random walk on the sets of integers  $\{0, 1, \dots, L\}$ . The walk jumps to the right or left at each step with probability  $1/2$  subject to the rule that if it tries to go to the left from 0 or to the right from  $L$  it stays put. Compute the stationary distribution of this random walk.
- Consider the following random walk on state-space  $\{0, 1, 2, \dots, L\}$  of numbers arranged on a ring. At each step, the walk goes to the right with probability  $a$  or to the left with probability  $1 - a$  subject to the rules if it tries to go to the left from 0 it ends up at  $L$  or if it tries to go to the right from  $L$  it ends up at 0. Compute the stationary distribution of this chain.

**Solution**

- By definition, since  $P$  is doubly stochastic,  $\sum_i P_{ij} = 1$  for all  $j$ . Trivially,

$$(qP)_j = \sum_{i=1}^N q_i P_{ij} = \sum_{i=1}^N \frac{1}{N} P_{ij} = \frac{1}{N} \sum_{i=1}^N P_{ij} = \frac{1}{N} = q_j$$

This proves  $qP = q$ . That is,  $q$  is a stationary distribution of  $P$ .

- We have probability transition matrix,

$$P = \begin{bmatrix} 1/2 & 1/2 & & & \\ 1/2 & & 1/2 & & \\ & 1/2 & & 1/2 & \\ & & 1/2 & & \ddots \\ & & & \ddots & & 1/2 \\ & & & & 1/2 & 1/2 \end{bmatrix}$$

This is doubly stochastic so it has an invariant distribution,

$$\pi = [1/L, 1/L, \dots, 1/L]$$

This is a finite irreducible chain so the stationary distribution is unique.

(c) We have probability transition matrix,

$$P = \begin{bmatrix} & 1/2 & & & 1/2 \\ 1/2 & & 1/2 & & \\ & 1/2 & & 1/2 & \\ & & 1/2 & & \ddots \\ & & & \ddots & & 1/2 \\ 1/2 & & & & & 1/2 \end{bmatrix}$$

This is doubly stochastic so it has an invariant distribution,

$$\pi = [1/L, 1/L, \dots, 1/L]$$

This is a finite irreducible chain so the stationary distribution is unique.

**Practice Exam 4, Problem 2**

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and a filtration  $\mathbb{F} = (\mathcal{F}_t)_{0 \leq t \leq T}$ . Suppose that  $X = (X_t)_{t \geq 0}$  satisfies the following SDE,

$$dX_t = -\kappa X_t dt + \sigma dW_t$$

where  $W$  is a  $(\mathbb{P}, \mathbb{F})$ -Brownian motion. Now consider a change of measure,

$$\frac{d\tilde{\mathbb{P}}}{d\mathbb{P}} = \exp\left(-\frac{1}{2}\gamma^2 T - \gamma W_T\right).$$

- (a) Derive an SDE for the process  $X$  under  $\tilde{\mathbb{P}}$ . Your answer should be given in terms of a process  $\tilde{W}$  which is a  $(\tilde{\mathbb{P}}, \mathbb{F})$ -Brownian motion.  
 (b) Define functions  $u : [0, T] \times \mathbb{R} \rightarrow \mathbb{R}$  and  $\tilde{u} : [0, T] \times \mathbb{R} \rightarrow \mathbb{R}$  as follows

$$u(t, x) := \mathbb{E}[h(X_T) | X_t = x], \quad \tilde{u}(t, x) := \tilde{\mathbb{E}}[h(X_T) | X_t = x]$$

Provide the PDEs satisfied by  $u$  and  $\tilde{u}$ , respectively.

**Solution**

- (a) By Girsanov's theorem we know that the process  $\tilde{W}$  defined as,

$$d\tilde{W}_t = \gamma dt + dW_t$$

is a Brownian motion under  $\tilde{\mathbb{P}}$ . Therefore, writing  $X$  in terms of this process we have,

$$dX_t = -\kappa X_t dt + \sigma \left( d\tilde{W}_t - \gamma dt \right) = -(\sigma\gamma + \kappa X_t) dt + \sigma d\tilde{W}_t$$

- (b) We have that  $u$  and  $\tilde{u}$  satisfy the KBE. In particular,

$$\left[ \left( \partial_t - \kappa \partial_x + \frac{1}{2} \sigma^2 \partial_x^2 \right) u(t, x) \right]_{x=X_t} = 0, \quad u(T, x) = h(x)$$

$$\left[ \left( \partial_t - (\sigma\gamma + \kappa x) \partial_x + \frac{1}{2} \sigma^2 \partial_x^2 \right) \tilde{u}(t, x) \right]_{x=X_t} = 0, \quad \tilde{u}(T, x) = h(x)$$

**Practice Exam 5, Problem 1**

Consider a Markov chain with state space  $\{0, 1, 2, \dots\}$  and transition probabilities,

$$\begin{aligned} p(i, i+1) &= p_i, & i \geq 0 \\ p(i, i-1) &= q_i, & i > 0 \\ p(i, i) &= r_i, & i \geq 0 \end{aligned}$$

For  $N > 0$  and state  $i$ , let  $a_N(i)$  be the probability that the time of first visit to state  $N$  is strictly less than the time of first visit to state 0 if we start at state  $i$ . Note that  $a_N(0) = 0$  and  $a_N(N) = 1$ .

- Write a recursive relation for  $a_N(i)$  by consider what happens on the first transition out of state  $i$ .
- Solve the above equation to compute  $a_N(i)$ .
- Use (b) above to show that state 0 is recurrent if and only if,

$$\sum_{j=1}^{\infty} \prod_{i=1}^{j-1} \frac{q_i}{p_i} = \infty$$

- Analyze the situation where  $p_i = p$ ,  $q_i = 1 - p$ ,  $r_i = 0$  for  $x \geq 1$ , and  $r_0 = 1 - p$ .

**Solution**

- Fix a state  $i \in \mathbb{Z}_+$ . If we transition down when we first leave  $i$ , the probability of reaching state  $N$  before state 0 is  $a_N(i-1)$ . Similarly, if we transition up when we first leave  $i$ , the probability of reaching state  $N$  before state 0 is  $a_N(i+1)$ .

The probability of transitioning up when leaving state  $i$  is  $p_i/(p_i + q_i)$  and the probability of transitioning down when leaving state  $i$  is  $q_i/(p_i + q_i)$ . We therefore have the relationship,

$$a_N(i) = \frac{p_i}{p_i + q_i} a_N(i+1) + \frac{q_i}{p_i + q_i} a_N(i-1)$$

- We solve this using Mathematica.

```
RSolve[{a[i] == ((p[i - 1] + q[i - 1]) a[i - 1] - q[i - 1] a[i - 2])/p[i - 1], a[0] == 0, a[n] == 1}, a[i], i]
```

This yields solution,

$$a_N(i) = \frac{\sum_{k=1}^i \prod_{j=1}^{k-1} \frac{q_j}{p_j}}{\sum_{k=1}^N \prod_{j=1}^{k-1} \frac{q_j}{p_j}}$$



(c) Define,

$$\tau_0 = \inf\{t > 0 : X_t = 0\}, \quad \tau_N = \inf\{t > 0 : X_t = N\}$$

By definition, state 0 is recurrent if and only if,

$$\mathbb{P}(\tau_0 < \infty | X_0 = 0) = \lim_{T \rightarrow \infty} \mathbb{P}(\tau_0 \leq T | X_0 = 0) = 1$$

Since, given  $X_0 = 0$ ,

$$\lim_{N \rightarrow \infty} \tau_N = \infty$$

State 0 is recurrent if and only if,

$$\lim_{N \rightarrow \infty} \mathbb{P}(\tau_0 \leq \tau_N | X_0 = 0) = 1$$

Taking the compliment we have that state 0 is recurrent if and only if,

$$\lim_{N \rightarrow \infty} \mathbb{P}(\tau_N < \tau_0 | X_0 = 0) = 0$$

In order to reach state  $N$  before returning to state 0, we must first move to state 1, and then reach state  $N$  before reaching state 0. We move from state 0 to state  $N$  with probability  $p_0$ , and we reach state  $N$  before state 0 from state 1 with probability  $a_N(1)$ . Therefore,

$$\mathbb{P}(\tau_N < \tau_0 | X_0 = 0) = \mathbb{P}(\tau_N < \tau_0) = p_0 a_N(1)$$

We then have that state 0 is recurrent if and only if,

$$\lim_{N \rightarrow \infty} p_0 a_N(1) = 0$$

Finally, we see that  $\lim_{N \rightarrow \infty} a_N(1) = 0$  if and only if,

$$\frac{1}{p_0} \sum_{k=1}^{\infty} \prod_{j=1}^{k-1} \frac{q_j}{p_j} = \lim_{N \rightarrow \infty} \frac{1}{p_0} \sum_{k=1}^N \prod_{j=1}^{k-1} \frac{q_j}{p_j} = \infty$$

(d) Let  $s = q/p$ . Then,

$$\frac{1}{p_0} \sum_{j=1}^{\infty} \prod_{i=1}^{j-1} \frac{q_i}{p_1} = \frac{1}{p} \sum_{j=1}^{\infty} s^{j-1} = \sum_{j=0}^{\infty} s^j$$

This is convergent if and only if  $q/p = s < 1$ . Therefore state 0 is recurrent if and only if  $q \geq p$  or  $p = 0$ .

**Practice Exam 5, Problem 2**

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and a filtration  $\mathbb{F} = (\mathcal{F}_t)_{t \geq 0}$ . Consider a mean-repelling OU process,

$$dX_t = X_t dt + \sqrt{2} dW_t$$

where  $W$  is a  $(\mathbb{P}, \mathbb{F})$ -Brownian motion.

- (a) Derive two representations of the transition density  $\Gamma(t, x, T, y) dy := \mathbb{P}(X_t \in dy | X_t = x)$  of  $X$ . One of the representations should involve Hermite polynomials.
- (b) Does the process  $X$  have an invariant distribution? If so, provide it. If not, explain why not.

**Solution**

- (a) Recall that  $X_t$  can be written explicitly in terms of  $W_t$  as,

$$X_T = e^{T-t} X_t + \int_t^T \sqrt{2} e^{T-s} dW_s$$

Recall that  $\int_t^T g(s) dW_s$  is normally distributed with mean zero and variance  $\int_t^T g(s)^2 ds$ . Therefore  $X_T$  is distributed normally with mean  $m(T, t, X_t) = e^{T-t} X_t$  and variance,

$$v(T, t, X_t) = \int_t^T \left( \sqrt{2} e^{T-s} \right)^2 ds = e^{2(T-t)} - 1$$

Therefore,

$$\Gamma(t, x, T, y) dy = \mathbb{P}(X_t \in dy | X_t = x) = \phi(y) dy$$

where  $\phi(y)$  is the density of a normal random variable with the above mean and variance  $m(T, t, x)$  and  $v(T, t, x)$  respectively.

Explicitly,

$$\Gamma(t, x, T, y) dy = \frac{dy}{\sqrt{2\pi (e^{2(T-t)} - 1)}} \exp \left( -\frac{1}{2} \frac{(y - x e^{T-t})^2}{e^{2(T-t)} - 1} \right)$$

---

We now compute  $\Gamma(t, x, T, y)$  by solving the KBE. In particular we have,

$$(\partial_t + \mathcal{A})\Gamma(t, x, T, y) = 0, \quad \Gamma(T, x, T, y) = \delta_y, \quad \mathcal{A} = x\partial_x + \partial_x^2$$

Write speed density,

$$m(x) = \exp\left(\int x dx\right) = \exp(x^2/2)$$

Suppose we have a complete set of eigenfunctions  $\psi_n$  of  $\mathcal{A}$  satisfying  $\mathcal{A}\psi_n = \lambda_n\psi_n$  normalized with respect to the speed density  $m(x)$ .

In this case,

$$\Gamma(t, x, T, y) = m(y) \sum_n e^{(T-t)\lambda_n} \psi_n(y) \psi_n(x)$$

We now find such eigenfunctions. Indeed,

*Note: Use forward equation to find eigenfunctions, then convert to eigenfunctions of backward equation*

Define,

$$\hat{\psi}_n(x) = e^{-x^2/2} H_n(x)$$

The Hermite polynomials have the properties,

$$H_{n+1} = xH_n - H'_n, \quad H'_n = nH_{n-1}$$

Therefore,

$$\hat{\psi}'_n = -xe^{-x^2/2} H_n + e^{-x^2/2} H'_n = (H'_n - xH_n)e^{-x^2/2} = -H_{n+1}e^{-x^2/2} = -\hat{\psi}_{n+1}$$

We then have,

$$\begin{aligned} x\hat{\psi}'_n &= -xH_{n+1}e^{-x^2/2} = -(H_{n+2} - H'_{n+1})e^{-x^2/2} = -\hat{\psi}_{n+2} + (n+1)\hat{\psi}_n \\ \hat{\psi}''_n &= \hat{\psi}_{n+2} \end{aligned}$$

Then,

$$\mathcal{A}\hat{\psi}_n = (n+1)\hat{\psi}_n$$

Now define,

$$\psi_n = \frac{\hat{\psi}_n}{\|\hat{\psi}_n\|_m}$$

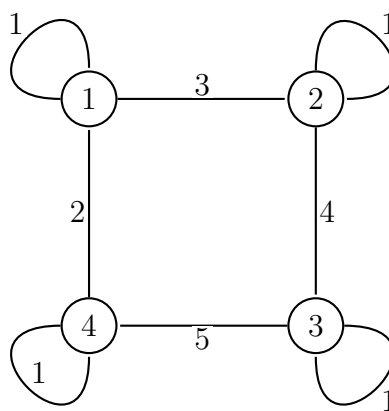
Finally *Note: argument about completeness*

(b) No.

Argument about spreading out.

**Practice Exam 6, Problem 1**

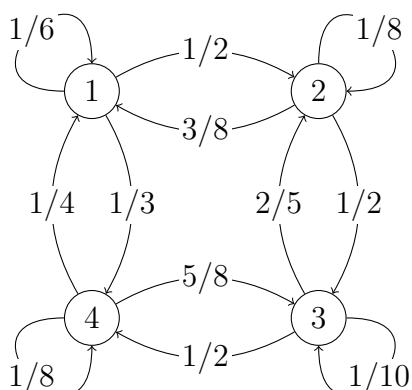
Consider a game which is played on a network with nodes numbered 1, 2, 3, 4 and edges that connect these nodes as show below. Note that each node in this network has self-loop edges. Every edge in the network has an associated weight. For example, the weight associated with the edge connecting nodes 1 and 2 is 3. Similarly the weight associated with the self-loop edge on node 1 is 1. The game proceeds as follows. You have a token that you move randomly from one node to another with probabilities propotional to the corresponding edge weights. For example, the probability that your token moves from node 1 to node 2 is  $3/(1 + 2 + 3) = 1/2$ . Let  $X_n$  be the position of your token after  $n$  moves, for  $n = 0, 1, 2, \dots$



- Model the stochastic process  $X_n$  as a Markov chain by drawing its state transition diagram and write the corresponding one-step transition probability matrix.
- Calculate the stationary distribution that your token is at node  $j$ , for  $j = 1, 2, 3, 4$ .
- Find the expected number of token moves between two consecutive visits to node 2.

**Solution**

- We have transition diagram,



The corresponding probability transition matrix  $P$  is,

$$P = \begin{bmatrix} 1/6 & 1/2 & 0 & 1/3 \\ 3/8 & 1/8 & 1/2 & 0 \\ 0 & 2/5 & 1/10 & 1/2 \\ 1/4 & 0 & 5/8 & 1/8 \end{bmatrix}$$

(b) We easily compute the right eigenvector corresponding to eigenvalue 1 as,

$$\pi = \frac{1}{4}[3/4, 1, 5/4, 1] = [3/16, 1/4, 5/16, 1/4]$$

(c) The expected number of moves is the mean recurrence time. This chain is irreducible so by theorem we have,

$$\tau_2 = 1/\pi(2) = 4$$

**Practice Exam 6, Problem 2**

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and a filtration  $\mathbb{F} = (\mathcal{F}_t)_{t \geq 0}$ . Let  $X$  be an OU process, and  $S$  a strictly increasing Lévy process (also known as a subordinator), whose dynamics are given by,

$$dX_t = -X_t dt + \sqrt{2} dW_t, \quad dS_t = \gamma dt + \int_0^\infty z N(dt, dz), \quad S_0 = 0$$

where  $W$  is a  $(\mathbb{P}, \mathbb{F})$ -Brownian motion and  $N$  is a poisson random measure with associated Lévy measure  $\nu$ . Consider a Subordinated OU process  $Y$  defined as follows,

$$Y_t = X_{S_t}$$

Define the two-parameter semigroup  $\mathcal{P}(t, T)$  associated with the  $Y$  process,

$$\mathcal{P}(t, T)f(y) := \mathbb{E}[f(Y_T)|Y_t = y]$$

For a fixed  $0 \leq t \leq T < \infty$ , what are the eigenfunctions and associated eigenvalues of the operator  $\mathcal{P}(t, T)$ ?

**Solution**

We first compute eigenvalues and eigenfunctions of  $\mathcal{Q}(t, T)$  defined by  $\mathcal{Q}(t, T)f(y) = \mathbb{E}[f(X_T)|X_t = x]$ .

We know that  $X$  has transition density,

$$\Gamma_X(t, x; T, y) = m(y) \sum_{n=0}^{\infty} H_n(x) H_n(y) e^{\lambda_n(T-t)}, \quad \lambda_n = n + 1$$

Therefore,

$$\mathcal{Q}(t, T)f(y) = \mathbb{E}[f(X_T)|X_t = x] = \int_{\mathbb{R}} f(y) \Gamma_X(t, x; T, y) dy$$

Now expanding the sum,

$$\begin{aligned} \mathcal{Q}(t, T)f(y) &= \int_{\mathbb{R}} f(y) m(y) \sum_{n=0}^{\infty} H_n(x) H_n(y) e^{\lambda_n(T-t)} dy \\ &= \sum_{n=0}^{\infty} H_n(x) e^{\lambda_n(T-t)} \int_{\mathbb{R}} f(y) H_n(y) m(y) dy \\ &= \sum_{n=0}^{\infty} H_n(x) e^{\lambda_n(T-t)} \langle f, H_n \rangle_m \end{aligned}$$



Now observe that for non-negative integer  $k$ , since  $\langle H_k, H_n \rangle = \delta_{k,n}$ ,

$$\mathcal{Q}(t, T)H_k(y) = \sum_{n=0}^{\infty} H_n(x) e^{\lambda_n(T-t)} \langle H_k, H_n \rangle_m = H_k(x) e^{\lambda_k(T-t)}$$

Therefore  $H_k$  is an eigenvector of  $\mathcal{Q}(t, T)$  with eigenvalue  $e^{\lambda_k(T-t)}$ .

Now observe,

$$\mathcal{P}(t, T)f(y) = \mathbb{E}[f(Y_T)|Y_t = y] = \mathbb{E}[f(X_{S_T})|X_{S_t} = y]$$

Now, by conditional averaging,

$$\mathcal{P}(t, T)f(y) = \mathbb{E}[\mathbb{E}[f(X_{S_T})|S_t, S_T, X_{S_t} = y]|X_{S_t} = y] = \mathbb{E}[\mathcal{Q}(S_t, S_T)f(y)|X_{S_t} = y]$$

Therefore,

$$\mathcal{P}(t, T)H_n(y) = \mathbb{E}[\mathcal{Q}(S_t, S_T)H_n(y)|X_{S_t} = y] = \mathbb{E}[e^{\lambda_n(S_T - S_t)} H_n(y)|X_{S_t} = y]$$

Let  $\phi(s) = \mathbb{E}[e^{isZ_{T-t}}]$  where  $Z_{T-t} = -iS_{T-t}$ . Then, using the stationary increments property of  $S$  and the fact that  $S_0 = 0$ ,

$$\mathcal{P}(t, T)H_n(y) = \mathbb{E}[e^{i\lambda_n S_{T-t}} H_n(y)|X_0 = y] = \phi(\lambda_n) H_n(y)$$

*Note: DID SOME SKETCHY SHIT HERE*

**Practice Exam 7, Problem 1**

- (a) (Weather chain) The weather can be either sunny, smoggy, or rainy. The weather stays sunny for an exponentially distributed amount of time with mean 3 days and then turns smoggy. It stays smoggy for an exponentially distributed amount of time with mean 4 days and then turns rainy. Finally, it rains for an exponentially distributed amount of time with mean 1 and then it is sunny. Model the weather system as a continuous time Markov chain and compute its stationary distribution.
- (b) (Barbershop) Consider a barbershop with one barber and two waiting chairs. The barber cuts hair at rate 3 customers per hour (exponentially distributed hair-cutting time). Customers arrive according to a Poisson process with rate 2 per hour. Arriving customers leave immediately if they find that the two waiting chairs are occupied. Model this system as a continuous time Markov chain and derive its stationary distribution.

**Solution**

- (a) Let the state space be  $\{1, 2, 3\}$  where 1 means sunny, 2 means smoggy, and 3 means rainy. By definition of the generator of the Markov process we have generator,

$$G = \begin{bmatrix} -1/3 & 1/3 & 0 \\ 0 & -1/4 & 1/4 \\ 1 & 0 & -1 \end{bmatrix}$$

We can easily verify that  $\pi G = 0$  if,

$$\pi = [3/8, 1/2, 1/8]$$

- (b) Let the state space  $\{0, 1, 2, 3\}$  denote the number of people in the queue. By definition of the generator of a Markov process we have generator,

$$G = \begin{bmatrix} -2 & 2 & & \\ 3 & -(3+2) & 2 & \\ & 3 & -(3+2) & 2 \\ & & 3 & -3 \end{bmatrix}$$

We can easily verify that  $\pi G = 0$  if,

$$\pi = [27, 18, 12, 8]/65$$

**Practice Exam 7, Problem 2**

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and a filtration  $\mathbb{F} = (\mathcal{F}_t)_{0 \leq t \leq T}$ . Consider two processes,

$$dX_t = \sigma_t dW_t, \quad dS_t = \sigma_t S_t dW_t$$

where  $W$  is a  $(\mathbb{P}, \mathbb{F})$ -Brownian motion and the process  $\sigma = (\sigma_t)_{0 \leq t \leq T}$  evolves independently of  $W$ .

(a) Show that,

$$\mathbb{E}[G(X_T - X_t) | \mathcal{F}_t] = \mathbb{E}[G(X_t - X_T) | \mathcal{F}_t]$$

(b) Show that,

$$\mathbb{E}[G(S_T) | \mathcal{F}_t] = \mathbb{E}[(S_T/S_t)G(S_t^2/S_T) | \mathcal{F}_t]$$

**Solution**

(a)

(b)

**Practice Exam 8, Problem 1**

A bakery uses a two-step process to make chocolate cakes. The first step involves baking the cake and the second step involves frosting the cake. Baking takes an exponentially distributed amount of time with rate  $\mu_1$ . After a cake is baked, it goes to the frosting machine. Frosting takes an exponentially distributed amount of time with rate  $\mu_2$ . The processing times at the oven and the frosting machine are independent random variables. Potential cakes arrive according to a Poisson process at rate  $\lambda$ , however, a cake goes to the baking oven only if both the oven and the frosting machine are idle. If any of the two is busy, the cake simply exits the system. We wish to model this system as a continuous-time Markov chain.

- (a) Precisely define the states of your continuous-time Markov chain (Hint: your model should have three states and note that there will never be two cakes in this system).
- (b) Draw a transition diagram for your continuous-time Markov chain.
- (c) Derive stationary distribution for your continuous-time Markov chain.
- (d) Find the expected number of cakes in this system in steady-state.

**Solution**

- (a)
- (b)

**Practice Exam 8, Problem 2**

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and a filtration  $\mathbb{F} = (\mathcal{F}_t)_{0 \leq t \leq T}$ . Define a process  $X$  and stopping time  $\tau$  as follows,

$$dX_t = \mu dt + \sigma dW_t, \quad \tau = \inf\{t \geq 0 : X_t \notin (a, b)\}$$

where  $W$  is a  $(\mathbb{P}, \mathbb{F})$ -Brownian motion. Define the following Laplace Transform,

$$L(x; \lambda) := \mathbb{E}[e^{-\lambda\tau} | X_0 = x], \quad x \in (a, b)$$

Derive the PDE satisfied by  $L$  and use this to find  $L$  explicitly.

**Solution**

(a)

(b)

## 11 Homework Problems

**Exercise 3.1**

Let  $X \sim \text{Bin}(n, U)$  where  $U \sim \mathcal{U}((0, 1))$ . What is the probability Generating function  $G_X(s)$  of  $X$ ? What is  $\mathbb{P}(X = k)$  where  $k \in \{0, 1, 2, \dots, n\}$ ?

**Solution**

Using iterated conditioning, since a Binomial random variable is the sum of  $n$  iid Bernioully random variables,

$$G_X(s) = \mathbb{E}[s^X] = \mathbb{E}\mathbb{E}[s^X|U] = \mathbb{E}[(1 - U)s^0 + Us^1]^n$$

We calculate this by integrating with Mathematica as,

```
Integrate[((1 - x) + x s)^n, {x, 0, 1}, Assumptions -> {s > 0}]
```

This yields,

$$\mathbb{E}[(1 - U) + Us]^n = \int_{\mathbb{R}} \mathbb{1}_{(0,1)}((1 - x) + xs)^n dx = \int_0^1 ((1 - x) + xs)^n dx = \frac{1 - s^{n+1}}{(n + 1)(1 - s)}$$

This is a finite geometric progression which we simplify so,

$$G_X(s) = \sum_{k=0}^n \frac{s^k}{n + 1}$$

Therefore  $\mathbb{P}(X = k) = 1/(n + 1)$  for  $k = 0, 1, 2, \dots, n$ .

**Exercise 3.2**

Let  $Z_n$  be the size of the  $n$ -th generation in an ordinary branching process with  $Z_0 = 1$ ,  $\mathbb{E}Z_1 = \mu$  and  $\mathbb{V}Z_1 > 0$ . Show that  $\mathbb{E}Z_n Z_m = \mu^{n-m} \mathbb{E}Z_m^2$  for  $m \leq n$ . Use this to find the correlation coefficient  $\rho(Z_m, Z_n)$  in terms of  $\mu, n$  and  $m$ . Consider the case  $\mu = 1$  and the case  $\mu \neq 1$ .

**Solution**

Let  $Y_{m,i}$  denote the number of offspring in the  $n$ -th generation that descends from the  $i$ -th member of the  $m$ -th generation. Then the  $(Y_{m,i})$  are iid with distribution  $Z_{n-m}$  and  $Z_n = Y_{m,1} + Y_{m,2} + \dots + Y_{m,Z_m}$ .

Then, since  $(Y_{m,i})$  are iid with distribution  $Z_{n-m}$ ,

$$\mathbb{E}[Z_n | Z_m] = \mathbb{E}[Y_{m,1} + Y_{m,2} + \dots + Y_{m,Z_m} | Z_m] = Z_m \mathbb{E}[Z_{n-m}] = Z_m \mu^{n-m}$$

Therefore, by taking out what is known,

$$\mathbb{E}[Z_m Z_n] = \mathbb{E}[\mathbb{E}[Z_m Z_n | Z_m]] = \mathbb{E}[Z_m^2 \mathbb{E}[Z_n | Z_m]] = \mathbb{E}[Z_m^2 \mu^{n-m}] = \mu^{n-m} \mathbb{E}[Z_m^2]$$

Observing that  $\mathbb{E}[Z_m Z_n] = \mu^{n-m} \mathbb{E}[Z_m^2] = \mu^{n-m} (\mathbb{V}[Z_m] + \mathbb{E}[Z_m]^2) = \mu^{n-m} (\mathbb{V}[Z_m] + \mu^{2m})$ , write,

$$\rho(Z_m, Z_n) = \frac{\text{Cov}(Z_n, Z_m)}{(\mathbb{V}[Z_n] \mathbb{V}[Z_m])^{1/2}} = \frac{\mathbb{E}[Z_n Z_m] - \mathbb{E}[Z_n] \mathbb{E}[Z_m]}{(\mathbb{V}[Z_n] \mathbb{V}[Z_m])^{1/2}} = \frac{\mu^{n-m} (\mathbb{V}[Z_m] + \mu^{2m}) - \mu^{n+m}}{(\mathbb{V}[Z_n] \mathbb{V}[Z_m])^{1/2}}$$

Denote  $\mathbb{V}[Z_1]$  by  $\sigma$ .

Suppose  $\mu = 1$  so that  $\mathbb{V}[Z_m] = m\sigma^2$ . We use Mathematica to simplify the above expression as,

```
FullSimplify[
  PowerExpand[(\[Mu]^(n - m) (Vzm + \[Mu]^(2 m)) - \[Mu]^(
    n + m)) / (Vzn Vzm)^(
    1/2) /. {Vzm -> m \[Sigma]^2, Vzn -> n \[Sigma]^2, \[Mu] ->
    1}],
  Assumptions -> {{m, n, \[Sigma], \[Mu]} > 0}]
```

This yields,

$$\rho(Z_m, Z_n) = \sqrt{\frac{m}{n}}$$



Now suppose  $\mu \neq 1$  so that  $\mathbb{V}[Z_m] = \sigma^2(\mu^n - 1)\mu^{n-1}/(\mu - 1)$ . We use Mathematica to simplify the above expression as,

```
FullSimplify[
  PowerExpand[(\[Mu]^(n - m) (Vzm + \[Mu]^(2 - m)) - \[Mu]^(
    n + m))/(Vzn Vzm)^(
    1/2) /. {Vzm -> \[Sigma]^2 (\[Mu]^m - 1) \[Mu]^(m - 1)/(\[Mu] -
    1),
    Vzn -> \[Sigma]^2 (\[Mu]^n - 1) \[Mu]^(n - 1)/(\[Mu] - 1) }],
  Assumptions -> {\[Mu] != 1, {m, n, \[Sigma], \[Mu]} > 0}]
```

This yields,

$$\rho(Z_m, Z_n) = \sqrt{\frac{\mu^n(\mu^m - 1)}{\mu^m(\mu^n - 1)}}$$

Observe that in the limit  $\mu \rightarrow 1$  this coincides with the previous value.

**Exercise 3.3****Solution**

**Exercise 3.4**

Consider a branching process with immigration

$$Z_0 = 1 \qquad Z_{n+1} = \sum_{i=1}^{Z_n} X_{n,i} + Y_n$$

where the  $(X_{n,i})$  are iid with common distribution  $X$ , the  $(Y_n)$  are iid with common distribution  $Y$ , and the  $(X_{n,i})$  and  $(Y_n)$  are independent. What is  $G_{Z_{n+1}}(s)$  in terms of  $G_{Z_n}(s)$ ,  $G_X(s)$ , and  $G_Y(s)$ ? Write  $G_{Z_2}(s)$  explicitly in terms of  $G_X(s)$  and  $G_Y(s)$ .

**Solution**

Define:

$$G_{Z_n}(s) = s^{Z_n} \qquad G_X(s) = \mathbb{E}s^X \qquad G_Y(s) = \mathbb{E}s^Y$$

Write  $S_n = \sum_{i=1}^{Z_n} X_{n,i}$  so that,  $Z_{n+1} = S_n + Y_n$ .

First observe that since the  $(X_{n,i})$  are iid with common distribution  $X$ ,

$$G_{S_n}(s) = \mathbb{E}[s^{S_n}] = \mathbb{E}[\mathbb{E}[s^{S_n}|Z_n]] = \mathbb{E}[\mathbb{E}[s^X]^{Z_n}] = \mathbb{E}[G_X(s)^{Z_n}] = G_{Z_n}(G_X(s))$$

Since the  $(X_{n,i})$  and  $(Y_n)$  are independent,  $S_n$  and  $Y_n$  are independent. Therefore,

$$G_{Z_{n+1}}(s) = G_{S_n+Y_n}(s) = G_{S_n}(s)G_Y(s) = G_{Z_n}(G_X(s))G_Y(s)$$

We calculate,

$$G_{Z_0}(s) = \mathbb{E}[s^{Z_0}] = \mathbb{E}[s] = s$$

Similarly,

$$G_{Z_1}(s) = G_{Z_0}(G_X(s))G_Y(s) = G_X(s)G_Y(s)$$

Therefore,

$$G_{Z_2}(s) = G_{Z_1}(G_X(s))G_Y(s) = G_X(G_X(s))G_Y(G_X(s))G_Y(s)$$

**Exercise 3.5**

Find  $\phi_{X^2}(t) := \mathbb{E} \exp(itX^2)$  where  $X \sim \mathcal{N}(\mu, \sigma)$ .

**Solution**

We have,

$$f_X(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right)$$

Thus,

$$\phi_{X^2}(t) = \mathbb{E} \exp(itX^2) = \int_{-\infty}^{\infty} e^{itx^2} f_X(x) dx$$

We evaluate with Mathematica as,

```
Integrate[Exp[I t x^2] PDF[NormalDistribution[\[Mu], \[Sigma]], x
], {x, -\[Infinity], \[Infinity]},
Assumptions -> {\[Mu] \[Element] Reals, t \[Element] Reals, \[
Sigma] > 0}]
```

This yields,

$$\phi_{X^2}(t) = \frac{\exp(it\mu^2/(1-2it\sigma^2))}{\sqrt{1-2it\sigma^2}}$$

**Exercise 3.6**

Let  $X_n$  have cumulative distribution function

$$F_{X_n}(x) = \left( x - \frac{\sin(2n\pi x)}{2n\pi} \right) \mathbb{1}_{0 \leq x \leq 1} + \mathbb{1}_{x > 1}$$

- (a) Show that  $F_{X_n}$  is a distribution function and find the corresponding density function  $f_{X_n}$ .
- (b) Show that  $F_{X_n}$  converges to the uniform distribution function  $F_U$  as  $n \rightarrow \infty$ , but that the density function  $f_{X_n}$  does NOT converge to  $f_U$ . Here,  $U \sim \mathcal{U}((0, 1))$ .

**Solution**

- (a) Clearly  $F_{X_n}(x) = 0$  for  $x \leq 0$  and  $F_{X_n}(x) = 1$  for  $x \geq 1$ . Observe,  $x - \sin(2n\pi x)/2n\pi$  is non-decreasing and continuous on  $(0, 1)$ , since the derivative, calculated below is non-negative on this interval. Moreover,  $x - \sin(2n\pi x)/2n\pi$  is equal to zero at  $x = 0$ , and equal to one at  $x = 1$ .

Therefore  $F_{X_n}(x)$  is a non-decreasing continuous function with  $F_{X_n}(x) \rightarrow 0$  as  $x \rightarrow -\infty$  and  $F_{X_n}(x) \rightarrow 1$  as  $x \rightarrow \infty$ . So  $F_{X_n}(x)$  is a distribution function.

It is straightforward to compute the density function as,

$$f_{X_n}(x) = \frac{d}{dx} F_{X_n}(x) = (1 - \cos(2n\pi x)) \mathbb{1}_{0 \leq x \leq 1}$$

- (b) The uniform distribution on  $(0, 1)$  is given by,

$$F_U(x) = x \mathbb{1}_{0 \leq x \leq 1} + \mathbb{1}_{x > 1}$$

Obviously outside of  $(0, 1)$  both  $F_U$  and  $F_{X_n}$  agree exactly. Consider a point  $x \in (0, 1)$ . Then, since  $|\sin(u)| \leq 1$  for all  $u$ ,

$$\lim_{n \rightarrow \infty} \left[ x - \frac{\sin(2n\pi x)}{2n\pi} \right] = x - 0 = x$$

Therefore  $F_{X_n}$  converges pointwise on to  $F_U$  on  $(0, 1)$ , and therefore on all of  $\mathbb{R}$ .

It is clear that  $f_{X_n}(x)$  does not converge to  $f_U(x)$  as  $f_U(x)$  is constant on  $(0, 1)$  while  $f_{X_n}(x)$  oscillates between zero and two. In particular, fix a rational number  $x = p/q$ . Then for  $n = qk, k \in \mathbb{N}$ ,  $f_{X_n}(x) = 0$ .

**Exercise 3.7**

A coin is tossed repeatedly, with heads turning up with probability  $p$  on each toss. Let  $N$  be the minimum number of tosses required to obtain  $k$  heads. Show that, as  $p \rightarrow 0$ , the distribution function of  $2Np$  converges to that of a gamma distribution. Note that, if  $X \sim \Gamma(\lambda, r)$  then,

$$f_X(x) = \frac{1}{\Gamma(r)} \lambda^r x^{r-1} e^{-\lambda x} \mathbb{1}_{x \geq 0}$$

**Solution**

We have  $\Gamma(r) = \int_0^\infty x^{r-1} e^{-x} dx$ . Thus, making the substitution  $u = (\lambda - it)x$ ,

$$\begin{aligned} \phi_X(t) &= \mathbb{E} [e^{itx} f_X(x) dx] \\ &= \int_0^\infty e^{itx} \frac{1}{\Gamma(r)} \lambda^r x^{r-1} e^{-\lambda x} dx \\ &= \int_0^\infty \frac{\lambda^r}{\Gamma(r)} e^{-u} \frac{u^{r-1}}{(\lambda - it)^{r-1}} \frac{du}{(\lambda - it)} \\ &= \frac{\lambda^r}{\Gamma(r)(\lambda - it)^r} \int_0^\infty e^{-u} u^{r-1} du \\ &= \frac{\lambda^r}{(\lambda - it)^r} \end{aligned}$$

Let  $(X_i)_{i=1}^k$  be iid with  $X, X_i \sim \text{Geo}(p)$ . Then  $N = \sum_{i=1}^k X_i$  so, since the  $X_i$  are iid,

$$\varphi_{2Np}(t) = \mathbb{E}[\exp(it2Np)] = \mathbb{E}[\exp(2itp(X_1 + \dots + X_k))] = \mathbb{E}[\exp(2itpX)]^k$$

Therefore, since  $|e^{2itp}(1-p)| < 1$  if  $p \in (0, 1)$ ,

$$\mathbb{E}[\exp(2itpX)]^k = \left[ \sum_{m=1}^{\infty} e^{2itpm} p(1-p)^{m-1} \right]^k = \left[ p e^{2itp} \sum_{m=1}^{\infty} (e^{2itp}(1-p))^{m-1} \right]^k = \left[ \frac{p e^{2itp}}{1 - (1-p)e^{2itp}} \right]^k$$

With Mathematica we evaluate,

```
Limit[((p Exp[2 I t p])/(1 - (1 - p) Exp[2 I t p]))^k, {p -> 0},
sumptions -> {k \[Element] Integers, k > 0}] // FullSimplify
```

This yields,

$$\lim_{p \rightarrow 0} \varphi_{2Np} = \frac{1}{(1 - 2it)^k} = \frac{(1/2)^k}{(1/2 - it)^k}$$

Thus, for a random variable  $X \sim \Gamma(1/2, k)$ , by the continuity theorem,  $\lim_{p \rightarrow 0} f_{2Np}(x) = f_X(x)$

**Exercise 4.1**

A six-sided die is rolled repeatedly. Which of the following are Markov chains? For those that are, find the one-step transition matrix.

- (a)  $X_n$  is the largest number rolled up to the  $n$ th roll.
- (b)  $X_n$  is the number of sixes rolled in the first  $n$  rolls.
- (c) At time  $n$ ,  $X_n$  is the time since the last six was rolled.
- (d) At time  $n$ ,  $X_n$  is the time until the next six is rolled.

**Solution**

- (a) Yes.

$$P = \begin{bmatrix} 1/6 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 \\ & 2/6 & 1/6 & 1/6 & 1/6 & 1/6 \\ & & 3/6 & 1/6 & 1/6 & 1/6 \\ & & & 4/6 & 1/6 & 1/6 \\ & & & & 5/6 & 1/6 \\ & & & & & 1 \end{bmatrix}$$

- (b) Yes.

$$P = \begin{bmatrix} 5/6 & 1/6 & & \\ & 5/6 & 1/6 & \\ & & \ddots & \ddots \end{bmatrix}$$

- (c) Yes. Suppose  $X_n = i$ . The next roll is either a 6, in which case  $X_{n+1} = 0$ . Otherwise  $X_{n+1} = i + 1$ .

$$P = \begin{bmatrix} 1/6 & 5/6 & & \\ 1/6 & & 5/6 & \\ 1/6 & & & 5/6 \\ \vdots & & & \ddots \end{bmatrix}$$

- (d) Yes. Suppose  $X_n = 0$ . The probability of  $X_{n+1} = j$  is  $(1/6)(5/6)^j$  as you must not roll a 6 for  $j$  turns, and then must roll a 6 on the  $j$ -th. Suppose  $X_n = i > 0$ . Then the next step you will be on turn closer to rolling a 6. That



is,  $X_{n+1} = i - 1$ .

$$P = \begin{bmatrix} \frac{1}{6} & \frac{1}{6} \left(\frac{5}{6}\right) & \frac{1}{6} \left(\frac{5}{6}\right)^2 & \frac{1}{6} \left(\frac{5}{6}\right)^3 & \dots \\ 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & \ddots \end{bmatrix}$$

**Exercise 4.2**

Let  $Y_n = X_{2n}$ . Compute the transition matrix for  $Y$  when

- (a)  $X$  is a simple random walk (i.e.,  $X$  increases by one with probability  $p$  and decreases by 1 with probability  $q$ )
- (b)  $X$  is a branching process where  $G$  is the generating function of the number of offspring from each individual

**Solution**

- (a) In each step we can go down with probability  $q$  and then down again with probability  $q$  or up with probability  $p$ . Alternatively we can go up with probability  $p$  and then down with probability  $q$  or up again with probability  $p$ .

Therefore we will end up two spaces down with probability  $q^2$ , in the same position with probability  $qp + pq = 2pq$ , or up two spaces with probability  $p^2$ . Thus,

$$p(i, j) = \begin{cases} p^2 & j = i + 2 \\ 2pq & i = j \\ q^2 & j = i - 2 \\ 0 & \text{otherwise} \end{cases}$$

- (b) We can obtain the exponents of a generating function  $G(s) = a_0 + a_1s + a_2s^2 + \dots$  by,

$$a_n = \frac{1}{n!} \frac{d^n}{ds^n} [G(s)]_{s=0}$$

The coefficient of the  $s^k$  term is the value of the probability mass function of  $X$  evaluated at  $k$ .

The generating function of  $Y$  is  $G(G(s)) = G_2(s)$  from the notes.

For a branching process with current population  $k$ , the population of the next generation will be  $X_1 + X_2 + \dots + X_k$ , where each  $X_i$  is iid with distribution  $X$ . Therefore,

$$p(i, j) = \frac{1}{j!} \frac{d^j}{ds^j} [G_2(s)^i]_{s=0}$$

**Exercise 4.3**

Let  $X$  be a Markov chain with state space  $S$  and absorbing state  $k$  (i.e.,  $p(k, j) = 0$  for all  $j \in S$ ). Suppose  $j \rightarrow k$  for all  $j \in S$ . Show that all states other than  $k$  are transient.

**Solution**

Fix a state  $j \in S$ . By definition of  $j \rightarrow k$ ,  $\exists N \geq 0 : p_N(j, k) > 0$ . Since  $\{X_N = k | X_0 = j\} \subseteq \{\exists n, X_n = k | X_0 = j\}$  we have,

$$0 < p_N(j, k) = \mathbb{P}(X_N = k | X_0 = j) \leq \mathbb{P}(\exists n, X_n = k | X_0 = j)$$

Therefore,

$$\mathbb{P}(\exists n \geq 0 : X_n = k | X_0 = j) = 1 - \mathbb{P}(\forall n, X_n \neq k | X_0 = j) < 1$$

This proves state  $j$  is transient. □

**Exercise 4.4**

Suppose two distinct states  $i, j$  satisfy

$$\mathbb{P}(\tau_j < \tau_i | X_0 = i) = \mathbb{P}(\tau_i < \tau_j | X_0 = j)$$

where  $\tau_j = \inf\{n \geq 1 : X_n = j\}$ . Show that, if  $X_0 = i$ , the expected value of visits to  $j$  prior to returning to  $i$  is one.

**Solution**

Write

$$p = \mathbb{P}(\tau_j < \tau_i | X_0 = i) = \mathbb{P}(\tau_i < \tau_j | X_0 = j)$$

That is,  $p$  is the probability that we go to state  $j$  before state  $i$  given we are in state  $i$ , and  $p$  is also the probability that we go to state  $i$  before state  $j$  given we are in state  $j$ .

Then  $1 - p$  is the probability that we do not go to state  $i$  before returning state  $j$ , given we start in state  $j$ .

So  $(1 - p)^k$  is the probability that we return to state  $j$  exactly  $k$  times before moving to state  $i$ , given we start in state  $j$ .

Let  $N$  be the number of visits to  $j$  prior to returning to  $i$  given we start in state  $i$ .

The probability that  $N = k \in \mathbb{Z}_{\geq 0}$  is the probability that starting from state  $i$  we go to state  $j$ , return to state  $j$   $(k - 1)$  times without returning to state  $i$ , and then return to state  $i$  without going to returning to state  $j$ .

So  $\mathbb{P}(N = k | X_0 = i) = p(1 - p)^{k-1}p$ . This is the probability mass function for  $N$  so,

$$\mathbb{E}[N] = \sum_{n=0}^{\infty} np^2(1 - p)^{k-1} = p \sum_{n=0}^{\infty} n(1 - p)^n = p \frac{p}{(1 - (1 - p))^2} = 1$$

**Exercise 4.5**

Let  $X$  be a Markov chain with transition matrix,

$$P = \begin{bmatrix} 1-2p & 2p & 0 \\ p & 1-2p & p \\ 0 & 2p & 1-2p \end{bmatrix}, \quad p \in (0, 1)$$

Find  $P^n$ , the invariant distribution  $\pi$ , and the mean-recurrence times  $\bar{\tau}_j$  for  $j = 1, 2, 3$ .

**Solution**

Note that  $P$  has eigendecomposition  $P = V\Lambda V^{-1}$  where,

$$\Lambda = \begin{bmatrix} 1 & & \\ & 1-4p & \\ & & 1-2p \end{bmatrix}, \quad V = \begin{bmatrix} 1 & 1 & -1 \\ 1 & -1 & 0 \\ 1 & 1 & 1 \end{bmatrix}$$

Therefore,  $P^n = V\Lambda^n V^{-1}$ . Explicitly,

$$P^n = \begin{bmatrix} 1 & 1 & -1 \\ 1 & -1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & & \\ & 1-4p & \\ & & 1-2p \end{bmatrix} \begin{bmatrix} 1/4 & 1/2 & 1/4 \\ 1/4 & -1/2 & 1/4 \\ -1/2 & 0 & 1/2 \end{bmatrix}$$

Invariant distributions are linear combinations of left eigenvectors corresponding to eigenvalues of 1. In this case that is the first row of  $V^{-1}$ . That is,

$$\pi = \begin{bmatrix} \frac{1}{4} & \frac{1}{2} \\ \frac{1}{4} & \end{bmatrix}$$

Finally, since the invariant distribution is unique, by Theorem we have,

$$\bar{\tau}_i = \frac{1}{\pi(i)}$$

**Exercise 4.6**

Let  $X_n$  be the number of mistakes in the  $n$ -th addition of a book. Between the  $n$ -th and the  $(n+1)$ -th addition an editor corrects each mistake independently with probability  $p$  and introduces  $Y_n$  new mistakes where the  $(Y_n)$  are iid and Poisson distributed with parameter  $\lambda$ . Find the invariant distribution  $\pi$  of the number of mistakes in the book.

**Solution**

Let  $M_{n,k}$  be distributed as  $\text{Ber}(1-p)$  so that  $M_k$  is 0 if this mistake is corrected, and 1 otherwise. Let  $Y_n$  be Poisson distributed with parameter  $\lambda$ . Then,

$$X_{n+1} = Y_n + \sum_{k=1}^{X_n} M_k$$

Each  $M_{n,k}$  has generating function,

$$G_{M_{n,k}} = p + (1-p)s = 1 - q + qs = 1 - q(1-s)$$

Similarly,  $Y_n$  has generating function,

$$G_Y(s) = \sum_{k=0}^{\infty} e^{-\lambda} \lambda^k / k! s^k = e^{-\lambda} e^{s\lambda} = e^{\lambda(s-1)}$$

Therefore  $X_{n+1}$  has generating function,

$$\begin{aligned} G_{n+1}(s) &= G_Y(s) \mathbb{E} [s^{M_{k,1} + M_{k,2} + \dots + M_{k,X_n}}] \\ &= G_Y(s) \mathbb{E} [\mathbb{E} [s^{M_{k,1} + M_{k,2} + \dots + M_{k,X_n}} | X_n]] \\ &= G_Y(s) \mathbb{E} [(1 - q(1-s))^{X_n}] \\ &= G_Y(s) G_n(1 - q(1-s)) \end{aligned}$$

First observe  $1 - q^i(1 - (1 - q(1-s))) = 1 - q^{i+1}(1-s)$ . We now use the relation

$G_{n+1}(s) = G_Y(s)G_n(1 - q(1 - s))$  and the fact that  $G_0(s) = 1$  to calculate,

$$\begin{aligned}
 G_{n+1}(s) &= G_Y(s)G_n(1 - q(1 - s)) \\
 &= G_Y(s)G_Y(1 - q(1 - s))G_{n-1}(1 - q^2(1 - s)) \\
 &= G_Y(s)G_Y(1 - q(1 - s))G_Y(1 - q^2(1 - s))G_{n-2}(1 - q^3(1 - s)) \\
 &\vdots \\
 &= \prod_{i=0}^n G_Y(1 - q^i(1 - s))
 \end{aligned}$$

Then,

$$\begin{aligned}
 \lim_{n \rightarrow \infty} G_n(s) &= \lim_{n \rightarrow \infty} G_{n+1}(s) \\
 &= \lim_{n \rightarrow \infty} \prod_{i=0}^n G_Y(1 - q^i(1 - s)) \\
 &= \lim_{n \rightarrow \infty} \prod_{i=0}^n \exp(\lambda(-q^i(1 - s))) \\
 &= \exp\left(\sum_{i=0}^{\infty} \lambda(-q^i(1 - s))\right) \\
 &= \exp\left(\lambda(s - 1)\frac{1}{1 - q}\right) \\
 &= \exp\left(\frac{\lambda}{p}(s - 1)\right)
 \end{aligned}$$

Thus,  $G_n(S)$  converges to the generating function of a Poisson random variable with parameter  $\lambda/p$ .

Then  $X_n$  converges to a random variable distributed like a Poisson random variable with parameter  $\lambda/p$ . The random variable for which  $X_n$  converges to must be the variable corresponding to the stationary distribution. Therefore, the stationary distribution is distributed like the probability mass function of this random variable. That is,

$$\pi(k) = e^{-\lambda/p} \frac{(\lambda/p)^k}{k!}$$

In the limit  $p \rightarrow 1$ , where we correct all mistakes, the stationary distribution looks like a Poisson distribution with parameter  $\lambda$ . In the limit  $\lambda \rightarrow 0$  so we do not make any new mistakes,  $\pi(0) \rightarrow 1$  as expected.

**Exercise 4.7**

Give an example of a transition matrix  $P$  that admits multiple stationary distributions  $\pi$ .

**Solution**

Define  $P$  to be the identity matrix. Then any distribution is a stationary distribution.



**Exercise 4.8**

A Markov chain on  $S = \{0, 1, 2, \dots, n\}$  has transition probabilities  $p(0, 0) = 1 - \lambda_0$ ,  $p(i, i+1) = \lambda_i$  and  $p(i+1, i) = \mu_{i+1}$  for  $i = 0, 1, \dots, n-1$ , and  $p(n, n) = 1 - \mu_n$ . Show that the process is reversible in equilibrium.

**Solution**

We assume all entries not specified are zero. (I heard this is the intent, however I wonder why we are given  $\mu_j$  when  $\mu_j = 1 - \lambda_j$  for all  $j$ ). We write the matrix  $P$  as, Write  $\mu_n = 1 - \lambda_n$ . Thus,  $\mu_i = 1 - \lambda_i$  for  $i = 1, \dots, n$  as the sum of each row must be 1 (making the assumption that all entries not specified at zero).

$$P = \begin{bmatrix} 1-\lambda_0 & \lambda_0 & & & \\ \mu_1 & & \lambda_1 & & \\ & \mu_2 & & \lambda_2 & \\ & & \mu_3 & & \\ & & & & \lambda_{n-1} \\ & & & \mu_n & 1-\mu_n \end{bmatrix} = \begin{bmatrix} 1-\lambda_0 & \lambda_0 & & & \\ 1-\lambda_1 & & \lambda_1 & & \\ & 1-\lambda_2 & & \lambda_2 & \\ & & 1-\lambda_3 & & \\ & & & & 1-\lambda_n & \lambda_{n-1} \end{bmatrix}$$

This chain is irreducible and finite so a unique invariant distribution  $\pi$  exists. Write  $\pi = [\pi_0, \pi_1, \dots, \pi_n]$ . Then  $\pi P = \pi$ . That is,

$$\pi P = \begin{bmatrix} \pi_0(1-\lambda_0) + \pi_1(1-\lambda_1) \\ \pi_0\lambda_0 + \pi_2(1-\lambda_2) \\ \pi_1\lambda_1 + \pi_3(1-\lambda_3) \\ \vdots \\ \vdots \\ \pi_{n-1}\lambda_{n-1} + \pi_n\lambda_n \end{bmatrix}^T = \begin{bmatrix} \pi_0 \\ \pi_1 \\ \pi_2 \\ \vdots \\ \pi_j \\ \vdots \\ \pi_n \end{bmatrix}^T$$

$$\begin{aligned} \pi_1 &= \lambda_0\pi_0/(1-\lambda_1) & \lambda_0\pi_0 &= \pi_1(1-\lambda_1) \\ \pi_2 &= (\pi_1 - \pi_0\lambda_0)/(1-\lambda_2) = \pi_1\lambda_1/(1-\lambda_2) & \lambda_1\pi_1 &= \pi_2(1-\lambda_2) \\ \pi_3 &= (\pi_2 - \pi_1\lambda_1)/(1-\lambda_3) = \pi_2\lambda_2/(1-\lambda_3) & \lambda_2\pi_2 &= \pi_3(1-\lambda_3) \\ &\vdots & & \\ \pi_{j+1} &= (\pi_j - \pi_{j-1}\lambda_{j-1})/(1-\lambda_{j+1}) = \pi_j\lambda_j/(1-\lambda_{j+1}) & \lambda_j\pi_j &= \pi_{j+1}(1-\lambda_{j+1}) \\ &\vdots & & \\ \pi_n &= (\pi_{n-1}\lambda_{n-1})/(1-\lambda_n) & \pi_{n-1}\lambda_{n-1} &= \pi_n(1-\lambda_n) \end{aligned}$$

Observing the equations on the right hand side we have that for  $i = 1, 2, \dots, n - 1$ ,

$$\pi_i p(i, i + 1) = \pi_{i+1} p(i + 1, i)$$

We now show the detail balance condition. In particular, we must show,

$$\pi_i p(i, j) = \pi_j p(j, i) \quad \text{for all } i, j$$

However, for  $j \notin \{i - 1, i + 1\}$  we have  $p(i, j) = 0$ . Therefore, for this matrix the previous condition is equivalent to

$$\pi_i p(i, i + 1) = \pi_{i+1} p(i + 1, i) \quad \text{for } i = 1, 2, \dots, n - 1$$

We have shown that these equations hold for all  $i = 1, 2, \dots, n - 1$ .

This proves  $\pi$  is in detailed balance with  $P$ , and so this process is reversible in equilibrium.  $\square$

**Exercise 5.1**

Patients arrive at an emergency room as a Poisson process with intensity  $\lambda$ . The time to treat each patient is an independent exponential random variable with parameter  $\mu$ . Let  $X = (X_t)_{t \geq 0}$  be the number of patients in the system (either being treated or waiting). Write down the generator of  $X$ . Show that  $X$  has an invariant distribution  $\pi$  if and only if  $\lambda < \mu$ . Find  $\pi$ . What is the total expected time (waiting + treatment) a patient waits when the system is in its invariant distribution?

**Solution**

In some small time interval  $s$  there is probability  $\lambda s + \mathcal{O}(s^2)$  that a patient arrives, probability  $1 - \lambda s + \mathcal{O}(s^2)$  that a patient does not arrive, and probability  $\mathcal{O}(s^2)$  that multiple patients arrive.

If there are patients, in this times there is also probability  $\mu s + \mathcal{O}(s^2)$  that a patient is treated, probability  $1 - \mu s + \mathcal{O}(s^2)$  that a patient is not treated, and probability  $\mathcal{O}(s^2)$  that more than one (if possible) patients are treated.

Note that any moves which have more than one transition such as a patient arriving, and a patient being treated are all  $\mathcal{O}(s^2)$ .

Suppose there are no patients at time  $t$ . The probability of transitioning to  $j$  patients after a short time  $s$  is given by,

$$\mathbb{P}(X_{t+s} = j | X_t = 0) = \begin{cases} \lambda s + \mathcal{O}(s^2) & j = 1 \\ 1 - \lambda s + \mathcal{O}(s^2) & j = 0 \\ \mathcal{O}(s^2) & \text{otherwise} \end{cases}$$

Now suppose there are  $i > 0$  patients at time  $t$ . The probability of transitioning to  $j$  patients after a short time  $s$  is given by,

$$\mathbb{P}(X_{t+s} = j | X_t = i) = \begin{cases} (\lambda s + \mathcal{O}(s^2))(1 - \mu s + \mathcal{O}(s^2)) & j = i + 1 \\ (1 - \lambda s + \mathcal{O}(s^2))(1 - \mu s + \mathcal{O}(s^2)) + \mathcal{O}(s^2) & j = i \\ (1 - \lambda s + \mathcal{O}(s^2))(\mu s + \mathcal{O}(s^2)) & j = i - 1 \\ \mathcal{O}(s^2) & \text{otherwise} \end{cases}$$

This is simplified as,

$$\mathbb{P}(X_{t+s} = j | X_t = i) = \begin{cases} \lambda s + \mathcal{O}(s^2) & j = i + 1 \\ 1 - \lambda s - \mu s + \mathcal{O}(s^2) & j = i \\ \mu s + \mathcal{O}(s^2) & j = i - 1 \\ \mathcal{O}(s^2) & \text{otherwise} \end{cases}$$

This gives,

$$G = \begin{bmatrix} -\lambda & \lambda & & & \\ \mu & -(\lambda + \mu) & \lambda & & \\ & \mu & -(\lambda + \mu) & \lambda & \\ & & \mu & -(\lambda + \mu) & \lambda & \cdots \\ & & & \vdots & \vdots & \ddots \end{bmatrix}$$

We recognize this as a birth-death process (a bit ironic in the context of an emergency room) with  $\lambda_i = \lambda$  and  $\mu_i = \mu$ .

Then if a stationary distribution  $\pi$  exists, for  $n \in \mathbb{Z}_{>0}$ ,

$$\pi(n > 0) = \left(\frac{\lambda}{\mu}\right)^n \pi(0)$$

and

$$\pi(0) = \left(1 + \sum_{n=1}^{\infty} \left(\frac{\lambda}{\mu}\right)^n\right)^{-1} = \left(\sum_{n=0}^{\infty} \left(\frac{\lambda}{\mu}\right)^n\right)^{-1}$$

This is a geometric series which is convergent exactly when  $\lambda/\mu < 1$ . That is, when  $\lambda < \mu$ . In this case,

$$\pi(0) = \left(\sum_{n=0}^{\infty} \left(\frac{\lambda}{\mu}\right)^n\right)^{-1} = \left(\frac{\mu}{\mu - \lambda}\right)^{-1} = \frac{\mu - \lambda}{\mu}$$

We condition on knowing the number of people on the queue. Suppose there are  $n$  people in the queue when a patient arrives. Then the patient will have to wait a random time distributed as the sum of  $n$  exponential random variables with parameter  $\mu$  to be treated and one more to finish treatment. The expectation of each of each exponential random variable is  $1/\mu$ , so the patient waits an expected time of  $(n+1)/\mu$ .

In equilibrium, the probability that there are  $n$  people in the queue when a patient arrives is  $\pi(n)$ .

Therefore, the expected wait time is,

$$\sum_{n=0}^{\infty} \pi(n) \frac{(n+1)}{\mu} = \frac{\mu - \lambda}{\mu^2} \sum_{n=0}^{\infty} \left(\frac{\lambda}{\mu}\right)^n (n+1) = \frac{\mu - \lambda}{\mu^2} \left(\frac{\mu\lambda}{(\mu - \lambda)^2} + \frac{\mu}{\mu - \lambda}\right) = \frac{1}{\mu - \lambda}$$

**Exercise 5.2**

Let  $X = (X_t)_{t \geq 0}$  be a Markov chain with stationary distribution  $\pi$ . Let  $N$  be an independent Poisson process with intensity  $\lambda$  and denote by  $\tau_n$  the time of the  $n$ -th arrival of  $N$ . Define  $Y_n := X_{\tau_n+}$  (i.e.,  $Y_n$  is the value of  $X$  immediately after the  $n$ -th jump). Show that  $Y$  is a discrete time Markov chain with the same stationary distribution as  $X$ .

It is obvious that  $Y$  is Markov, as given the present, the future is independent of the past. We add a bit more rigor below.

Fix a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$ . By hypothesis  $X_t$  is a Markov process. That is, for a filtration  $(\mathcal{F}_s)_{s \in [0, T]}$ , for  $0 \leq s \leq t \leq T$ , and for every non-negative Borel measurable function  $f$ ,

$$\mathbb{E}[f(X_t) | \mathcal{F}_s] = \mathbb{E}[f(X_t) | X_s]$$

Let  $\mathcal{F}'_n = \mathcal{F}_{\tau_n+}$  be a sub- $\sigma$ -algebra of  $\mathcal{F}$ . Then clearly  $(\mathcal{F}'_n)$  is a filtration. Let  $f$  be any non-negative Borel measurable function. Then,

$$\mathbb{E}[f(Y_n) | \mathcal{F}'_m] = \mathbb{E}[f(X_{\tau_n+}) | \mathcal{F}_{\tau_m+}] = \mathbb{E}[f(X_{\tau_n+}) | X_{\tau_m+}] = \mathbb{E}[f(Y_n) | Y_m]$$

This means  $Y$  is Markov, and clearly  $Y$  is discrete time. Therefore  $Y$  is a discrete time Markov chain.

Note we assume  $X$  is time homogeneous.

Suppose  $X$  has stationary distribution  $\pi$ . Then for all  $0 \leq t \leq T$ ,  $\pi P_t = \pi$ , where,

$$(P_t)_{i,j} = \mathbb{P}(X_t = j | X_0 = i)$$

Thus, the one step probability transition matrix, denoted  $\tilde{P}$ , for  $Y$  is,

$$\tilde{P}_{i,j} = \mathbb{P}(Y_1 = j | Y_0 = i) = \mathbb{P}(X_{\tau_1+} = j | X_0 = i) = (P_{\tau_1})_{i,j}$$

This means  $\pi \tilde{P} = \pi$ , so  $\pi$  is a stationary distribution of  $Y$ .

**Exercise 5.3**

Let  $X = (X_t)_{t \geq 0}$  be a Markov chain with state space  $S = \{0, 1, 2, \dots\}$  and generator  $G$  whose  $i$ -th row has entries

$$g_{i,i-1} = i\mu \qquad g_{i,i} = -i\mu - \lambda \qquad g_{i,i+1} = \lambda,$$

with all other entries being zero (the zeroth row has only two entries:  $g_{0,0}$  and  $g_{0,1}$ ). Assume  $X_0 = j$ . Find  $G_{X_t}(s) := \mathbb{E}s^{X_t}$ . What is the distribution of  $X_t$  as  $t \rightarrow \infty$ ?

**Solution**

We have  $G$  in matrix form,

$$G = \begin{bmatrix} -\lambda & \lambda & & & & \\ \mu & -(\mu + \lambda) & \lambda & & & \\ & 2\mu & -(2\mu + \lambda) & \lambda & & \\ & & 3\mu & -3(\mu + \lambda) & \lambda & \cdots \\ & & & \vdots & \vdots & \ddots \end{bmatrix}$$

We wish to find the transition semi group  $P_t$ . We know this can be derived from the Kolmogorov forward equations. That is,

$$\frac{d}{dt}P_t = P_t G$$

With the assumption that  $X_0 = i$  (*I am using  $i$  rather than  $j$  like the problem statement since this is the standard way of doing things*) we have,

$$\begin{aligned} \frac{d}{dt}p_t(i, 0) &= \sum_{k=0}^{\infty} p_t(i, k)g(k, 0) = -\lambda p_t(i, 0) + \mu p_t(i, 1) \\ \frac{d}{dt}p_t(i, j) &= \sum_{k=0}^{\infty} p_t(i, k)g_t(k, j) = \lambda p_t(i, j-1) - (j\mu + \lambda)p_t(i, j) + (j+1)\mu p_t(i, j+1) \end{aligned}$$

$j \geq 1$

We multiply the  $j$ -th equation by  $s^j$ . This gives,

$$\sum_{j=0}^{\infty} \frac{\partial}{\partial t} p_t(i, j) s^j = \sum_{j=1}^{\infty} [\lambda p_t(i, j-1) s^j] - \sum_{j=0}^{\infty} [(j\mu + \lambda) p_t(i, j) s^j] + \sum_{j=0}^{\infty} [(j+1)\mu p_t(i, j+1) s^j]$$

Summing the left hand sides gives,

$$\sum_{j=0}^{\infty} \frac{\partial}{\partial t} p_t(i, j) s^j = \frac{\partial}{\partial t} \sum_{j=0}^{\infty} p_t(i, j) s^j = \frac{\partial}{\partial t} G_{X_t}(s)$$

The first term of the right hand side gives,

$$\sum_{j=1}^{\infty} \lambda p_t(i, j-1) s^j = \lambda s \sum_{j=1}^{\infty} p_t(i, j-1) s^{j-1} = \lambda s \sum_{j=0}^{\infty} p_t(i, j) s^j = \lambda s G_{X_t}(s)$$

The negative of the first part of the second term of the right hand side gives,

$$\sum_{j=0}^{\infty} j \mu p_t(i, j) s^j = s \mu \sum_{j=0}^{\infty} j p_t(i, j) s^{j-1} = s \mu \sum_{j=0}^{\infty} \frac{\partial}{\partial s} p_t(i, j) s^j = s \mu \frac{\partial}{\partial s} \sum_{j=0}^{\infty} p_t(i, j) s^j = s \mu \frac{\partial}{\partial s} G_{X_t}(s)$$

The negative of the second part of the second term of the right hand side gives,

$$\sum_{j=0}^{\infty} \lambda p_t(i, j) s^j = \lambda \sum_{j=0}^{\infty} p_t(i, j) s^j = \lambda G_{X_t}(s)$$

The third term of the right hand side gives,

$$\sum_{j=1}^{\infty} (j+1) \mu p_t(i, j+1) s^j = \mu \sum_{j=1}^{\infty} \frac{\partial}{\partial s} p_t(i, j+1) s^{j+1} = \mu \frac{\partial}{\partial s} \sum_{j=0}^{\infty} p_t(i, j) s^j = \mu \frac{\partial}{\partial s} G_{X_t}(s)$$

Putting these results together we have,

$$\frac{\partial}{\partial t} G_{X_t}(s) = \left[ \lambda s - s \mu \frac{\partial}{\partial s} - \lambda + \mu \frac{\partial}{\partial s} \right] G_{X_t}(s)$$

Since  $X_0 = j$  we have initial condition,

$$G_{X_0}(s) = s^j$$

We solve with Mathematica by,

```
DSolve[{
  D[G[s,t],t]==\[Lambda] s G[s,t]-s \[Mu] D[G[s,t],s]-\[Lambda]
  G[s,t]+\[Mu] D[G[s,t],s],
  G[s,0]==s^j
},G[s,t],{s,t}]/FullSimplify
```

This yields,

$$G_{X_t}(s) = ((s-1)e^{-\mu t} + 1)^j \exp \left[ \frac{\lambda(s-1)e^{\mu(-t)}(e^{\mu t} - 1)}{\mu} \right]$$

We find the limit as  $t \rightarrow \infty$  with Mathematica by,

```
Limit[E^((E^(-t \[Mu]) (-1+E^(t \[Mu])) (-1+s) \[Lambda])/\[Mu])
      (1+E^(-t \[Mu]) (-1+s))^j, {t->\[Infinity]}, Assumptions->{\[
      Lambda]>0, \[Mu]>0}]
```

This yields,

$$G_{X_\infty}(s) = \lim_{t \rightarrow \infty} G_{X_t}(s) = e^{\frac{\lambda}{\mu}(s-1)}$$

So  $X_\infty = \lim_{t \rightarrow \infty} X_t$  is a Poisson random variable with parameter  $\lambda/\mu$ .



**Exercise 5.4**

Let  $N$  be a time-inhomogeneous Poisson process with intensity function  $\lambda(t)$ . That is, the probability of a jump of size one in the time interval  $(t, t + dt)$  is  $\lambda(t)dt$  and the probability of two jumps in that interval of time is  $\mathcal{O}(dt^2)$ . Write down the Kolmogorov forward and backward equations of  $N$  and solve them. Let  $N_0 = 0$  and let  $\tau_1$  be the time of the first jump of  $N$ . If  $\lambda(t) = c/(1+t)$  show that  $\mathbb{E}\tau_1 < \infty$  if and only if  $c > 1$ .

**Solution**

Based on the definition of the generator and the given transition probabilities we have,

$$G(t) = \begin{bmatrix} -\lambda(t) & \lambda(t) & & & \\ & -\lambda(t) & \lambda(t) & & \\ & & -\lambda(t) & \lambda(t) & \cdots \\ & & & \vdots & \vdots & \ddots \end{bmatrix}$$

For  $t \geq s$  we define,

$$p_{s,t}(i, j) = \mathbb{P}(N_t = j | N_s = i)$$

We first derive the Kolmogorov forward equations. We consider,

$$\begin{aligned} p_{s,t+\Delta t} &= \mathbb{P}(N_{t+\Delta t} = j | N_s = i) \\ &= \sum_k \mathbb{P}(N_{t+\Delta t} = j | N_t = k) \mathbb{P}(N_t = k | N_s = i) \\ &= \begin{cases} \lambda(t)\Delta t p_{s,t}(i, j-1) + (1 - \lambda(t)\Delta t)p_{s,t}(i, j) + \mathcal{O}(\Delta t^2) & j > i \\ (1 - \lambda(t)\Delta t)p_{s,t}(i, j) + \mathcal{O}(\Delta t^2) & j = i \\ 0 & j < i \end{cases} \end{aligned}$$

Therefore,

$$\frac{p_{s,t+\Delta t}(i, j) - p_{s,t}(i, j)}{\Delta t} = \begin{cases} \lambda(t)\Delta t p_{s,t}(i, j-1) - \lambda(t)\Delta t p_{s,t}(i, j) + \mathcal{O}(\Delta t^2) & j > i \\ -\lambda(t)\Delta t p_{s,t}(i, j) + \mathcal{O}(\Delta t^2) & j = i \\ 0 & j < i \end{cases}$$

Taking the limit as  $\Delta t \rightarrow 0$  we have,

$$\frac{\partial}{\partial t} p_{s,t}(i, j) = \begin{cases} \lambda(t)p_{s,t}(i, j-1) - \lambda(t)p_{s,t}(i, j) & j > i \\ -\lambda(t)p_{s,t}(i, j) & j = i \\ 0 & j < i \end{cases}$$

Fix  $i$ . Noting that  $G_F(x)$  is also a function of  $s, t$  and  $j$ , we have,

$$G_F(x) = \sum_{j=0}^{\infty} \mathbb{P}(N_t = j | N_s = i) x^j = \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j$$

Thus, multiplying the  $j$ -th KFE by  $x^j$  and summing, we have,

$$\begin{aligned} \frac{\partial}{\partial t} \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j &= \sum_{j=i}^{\infty} \frac{\partial}{\partial t} p_{s,t}(i, j) x^j = \sum_{j=i+1}^{\infty} \lambda(t) p_{s,t}(i, j-1) x^j + \sum_{j=i}^{\infty} (-\lambda(t)) p_{s,t}(i, j) x^j \\ &= \lambda(t) x \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j - \lambda(t) \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j \end{aligned}$$

Therefore,

$$\frac{\partial}{\partial t} G_F(x) = \lambda(t) x G_F(x) - \lambda(t) G_F(x) = \lambda(t) (x - 1) G_F(x)$$

We have initial condition  $N_s = i$ , so  $G_B(x) = x^i$  when  $s = t$ .

We solve with Mathematica as,

```
DSolve[{D[G[s, t], t] == \[Lambda][t] (x - 1) G[s, t],
  G[s, s] == x^i
}, G[s, t], {s, t}] // FullSimplify
```

This gives,

$$G_F(x) = x^i \exp \left( (x - 1) \int_s^t \lambda(z) dz \right)$$

Write  $I = \int_s^t \lambda(z) dz$ . Then,

$$G_F(x) = e^{-I} x^i e^{Ix} = e^{-I} x^i \sum_{k=0}^{\infty} \frac{1}{k!} (Ix)^k = e^{-I} \sum_{k=0}^{\infty} \frac{1}{k!} I^k x^{k+i} = e^{-I} \sum_{j=i}^{\infty} \frac{I^{j-i}}{(j-i)!} x^j$$

Therefore, from the definition of the Generating function we have,

$$P_{s,t}(i, j) = \mathbb{P}(N_t = j | N_s = i) = \frac{1}{(j-i)!} \left[ \int_s^t \lambda(z) dz \right]^{j-i} \exp \left( - \int_s^t \lambda(z) dz \right)$$

We now derive the Kolmogorov Backward equations. We consider,

$$\begin{aligned} p_{s-\Delta s, t} &= \mathbb{P}(N_t = j | N_{s-\Delta s} = i) \\ &= \sum_k \mathbb{P}(N_t = j | N_s = k) \mathbb{P}(N_s = k | N_{s-\Delta s} = i) \\ &= \begin{cases} \lambda(s) \Delta s p_{s,t}(i+1, j) + (1 - \lambda(s) \Delta s) p_{s,t}(i, j) + \mathcal{O}(\Delta s^2) & j > i \\ (1 - \lambda(s) \Delta s) p_{s,t}(i, j) + \mathcal{O}(\Delta s^2) & j = i \\ 0 & j < i \end{cases} \end{aligned}$$

Therefore,

$$\frac{p_{s-\Delta s, t}(i, j) - p_{s,t}(i, j)}{\Delta s} = \begin{cases} \lambda(s) \Delta t p_{s,t}(i+1, j) - \lambda(s) \Delta t p_{s,t}(i, j) + \mathcal{O}(\Delta s^2) & j > i \\ -\lambda(s) \Delta t p_{s,t}(i, j) + \mathcal{O}(\Delta s^2) & j = i \\ 0 & j < i \end{cases}$$

Taking the limit as  $\Delta s \rightarrow 0$  we have,

$$-\frac{\partial}{\partial s} p_{s,t}(i, j) = \begin{cases} \lambda(s) p_{s,t}(i+1, j) - \lambda(s) p_{s,t}(i, j) & j > i \\ -\lambda(s) p_{s,t}(i, j) & j = i \\ 0 & j < i \end{cases}$$

Fix  $i$ . Noting that  $G_B(x)$  is also a function of  $s, t$  and  $j$ , we have,

$$G_B(x) = \sum_{j=0}^{\infty} \mathbb{P}(N_t = j | N_s = i) x^j = \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j$$

Thus, multiplying the  $j$ -th KBE by  $x^j$  and summing, we have,

$$\begin{aligned}
 -\frac{\partial}{\partial s} \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j &= -\sum_{j=i}^{\infty} \frac{\partial}{\partial s} p_{s,t}(i, j) x^j = \sum_{j=i+1}^{\infty} \lambda(s) p_{s,t}(i+1, j) x^j + \sum_{j=i}^{\infty} (-\lambda(s)) p_{s,t}(i, j) x^j \\
 &= \sum_{j=i+1}^{\infty} \lambda(s) p_{s,t}(i, j-1) x^j + \sum_{j=i}^{\infty} (-\lambda(s)) p_{s,t}(i, j) x^j \\
 &= \lambda(s) x \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j - \lambda(s) \sum_{j=i}^{\infty} p_{s,t}(i, j) x^j
 \end{aligned}$$

Therefore,

$$\frac{\partial}{\partial s} G_B(x) = -\lambda(s) x G_B(x) + \lambda(s) G_B(x) = -\lambda(s)(x-1) G_B(x)$$

From the result for  $G_F(x)$  we know,

$$G_B(x) = x^i \exp \left( -(x-1) \int_t^s \lambda(z) dz \right) = x^i \exp \left( (x-1) \int_s^t \lambda(z) dz \right) = G_F(x)$$

We now show that for  $\lambda(t) = c/(1+t)$ , that  $\mathbb{E}\tau_1 < \infty$  if and only if  $c < 1$ . Indeed,

$$\int_0^t \lambda(z) dz = \int_0^t \frac{c}{1+z} dz = c \ln(1+t) - c \ln(1) = c \ln(1+t)$$

Therefore,

$$\mathbb{E}[\tau_1] = \int_0^{\infty} \mathbb{P}(\tau_1 > t) dt = \int_0^{\infty} \mathbb{P}(N_t = 0 | N_0 = 0) dt = \int_0^{\infty} \exp(-c \ln(1+t)) dt = \int_0^{\infty} \frac{dt}{(1+t)^c}$$

This is convergent if and only if  $c > 1$ .

**Exercise 5.5**

Let  $N_t$  be a Poisson process with a random intensity  $\Lambda$  which is equal to  $\lambda_1$  with probability  $p$  and  $\lambda_2$  with probability  $1 - p$ . Find  $G_{N_t}(s) = \mathbb{E}s^{N_t}$ . What is the mean and variance of  $N_t$ ?

**Solution**

Recall the generating function for a Poisson process with intensity  $\lambda$  is,

$$G(s) = e^{-\lambda t(1-s)}$$

Therefore,

$$G_{N_t}(s) = \mathbb{E}[s^{N_t}] = \mathbb{E}[\mathbb{E}[s^{N_t}] | \Lambda] = \mathbb{E}[e^{-\Lambda t(1-s)} | \Lambda] = pe^{-\lambda_1 t(1-s)} + (1-p)e^{-\lambda_2 t(1-s)}$$

We use Mathematica to calculate moments,

```
GNt[s_]:=p Exp[-\[Lambda]1 t (1-s)]+(1-p)Exp[-\[Lambda]2 t (1-s)]
D[GNt[s],{s,1}]/.{s->1}
D[GNt[s],{s,2}]-D[GNt[s],{s,1}]^2+D[GNt[s],{s,1}]/.{s->1}
```

This yields,

$$\begin{aligned}\mu &= G'_{N_t}(1) = p\lambda_1 t + (1-p)\lambda_2 t \\ \sigma^2 &= G''_{N_t}(1) - [G'_{N_t}(1)]^2 + G'_{N_t}(1) = p(\lambda_1 t)^2 + (1-p)(\lambda_2 t)^2 - \mu^2 + \mu\end{aligned}$$

**Exercise 7.1**

Let  $W$  be a Brownian motion and let  $\mathbb{F} = (\mathcal{F}_t)_{t \geq 0}$  be a filtration for  $W$ . Show that  $W(t)^2 - t$  is a martingale with respect to the filtration  $\mathbb{F}$ .

**Solution**

Suppose  $X \sim \mathcal{N}(0, \sigma^2)$ . Then,

$$\sigma^2 = \mathbb{V}[X] = \mathbb{E}[X^2] - \mathbb{E}[X]^2 = \mathbb{E}[X^2] - 0^2 = \mathbb{E}[X^2]$$

Let  $0 \leq s \leq t$ . By the definition of a filtration,  $(W(t) - W(s))$  is independent of  $\mathcal{F}_s$ . Moreover, by the definition of Brownian Motion we have  $W(t) - W(s) \sim \mathcal{N}(0, t - s)$ . Thus,

$$\mathbb{E}[(W(t) - W(s))^2 | \mathcal{F}_s] = \mathbb{E}[(W(t) - W(s))^2] = (t - s)$$

Since  $W(s) \in \mathcal{F}_s$ , by “taking out what is known” we have,

$$\begin{aligned} \mathbb{E}[W(t)W(s) | \mathcal{F}_s] &= W(s)\mathbb{E}[W(t) | \mathcal{F}_s] = W(s)W(s) = W(s)^2 \\ \mathbb{E}[W(s)^2 | \mathcal{F}_2] &= W(s)\mathbb{E}[W(s) | \mathcal{F}_2] = W(s)W(s) = W(s)^2 \end{aligned}$$

Therefore,

$$\begin{aligned} \mathbb{E}[W(t)^2 - t | \mathcal{F}_s] &= \mathbb{E}[(W(t) - W(s) + W(s))^2 - t] \\ &= \mathbb{E}[(W(t) - W(s))^2 + 2(W(t) - W(s))W(s) + W(s)^2 - t] \\ &= \mathbb{E}[(W(t) - W(s))^2 | \mathcal{F}_s] + 2\mathbb{E}[W(t)W(s) | \mathcal{F}_s] - \mathbb{E}[W(s)^2 | \mathcal{F}_2] - \mathbb{E}[t] \\ &= (t - s) + 2W(s)^2 - W(s)^2 - t \\ &= W(s)^2 - s \end{aligned}$$

This proves  $W(t) - t$  is a martingale with respect to the filtration  $\mathbb{F}$ . □

**Exercise 7.2**

Compute the characteristic function of  $W(N(t))$  where  $N$  is a Poisson process with intensity  $\lambda$  and the Brownian motion  $W$  is independent of the Poisson process  $N$ .

**Solution**

The characteristic function is defined as,

$$\phi(s) = \mathbb{E} e^{isW(N(t))}$$

We condition on  $N(t)$  using iterated conditioning,

$$\mathbb{E} [e^{isW(N(t))}] = \mathbb{E} \left[ \mathbb{E} [e^{isW(N(t))} | N(t)] \right]$$

The characteristic function of  $Z \sim \mathcal{N}(\mu, \sigma^2)$  is  $\phi_Z(s) = \exp(i\mu s - \sigma^2 s^2/2)$ . At time  $t$ ,  $W(t)$  is normally distributed with mean zero and variance  $t$ . Thus,

$$\mathbb{E} \left[ \mathbb{E} [e^{isW(N(t))} | N(t)] \right] = \mathbb{E} [e^{-N(t)s^2/2}]$$

Since  $N(t)$  is a Poisson process with parameter  $\lambda$ , then  $N(t) = k$  with probability  $(\lambda t)^k e^{-\lambda t} / k!$ . Thus,

$$\mathbb{E} [e^{-N(t)s^2/2}] = \sum_{k=0}^{\infty} \frac{(\lambda t)^k}{k!} e^{-\lambda t} e^{-ks^2/2} = e^{-\lambda t} \sum_{k=0}^{\infty} \frac{(\lambda t)^k}{k!} \left( e^{-s^2/2} \right)^k$$

Simplifying yields,

$$e^{-\lambda t} \sum_{k=0}^{\infty} \frac{(\lambda t)^k}{k!} \left( e^{-s^2/2} \right)^k = e^{-\lambda t} \sum_{k=0}^{\infty} \frac{1}{k!} \left( \lambda t e^{-s^2/2} \right)^k = e^{-\lambda t} \exp \left( \lambda t e^{-s^2/2} \right) = \exp \left( \lambda t \left( e^{-s^2/2} - 1 \right) \right)$$

That is, the characteristic function  $\phi(s)$  of  $W(N(t))$  is,

$$\phi(s) = \exp \left( \lambda t \left( e^{-s^2/2} - 1 \right) \right)$$

**Exercise 7.3**

The  $n$ -th variation of a function  $f$ , over the interval  $[0, T]$  is defined as,

$$V_T(n, f) := \lim_{\|\Pi\| \rightarrow 0} \sum_{j=0}^{m-1} |f(t_{j+1}) - f(t_j)|^n, \quad \Pi = \{0 = t_0, t_1, \dots, t_m = T\}, \quad \|\Pi\| = \max_j (t_{j+1} - t_j)$$

Show that  $V_T(1, W) = \infty$  and  $V_T(3, W) = 0$ , where  $W$  is a Brownian motion.

**Solution**

We first prove that if  $f_n \rightarrow 0$  and  $|g_n| \leq M$  for some  $|M| < \infty$  then  $(f_n g_n) \rightarrow 0$ .

Indeed, fix  $\varepsilon > 0$ . Then, by convergence of  $f_n$  there is some  $N \in \mathbb{N}$  such that  $|f_n| < \varepsilon/M$  for all  $n \geq N$ . Then,

$$|f_n g_n| = |f_n| |g_n| \leq |f_n| M < (\varepsilon/M) M = \varepsilon$$

This proves  $f_n g_n \rightarrow 0$ . □

Write,

$$V_T(k+1, W) = \lim_{\|\Pi\| \rightarrow 0} \sum_{j=0}^{m-1} |W(t_{j+1}) - W(t_j)|^{k+1} = \lim_{\|\Pi\| \rightarrow 0} \sum_{j=0}^{m-1} |W(t_{j+1}) - W(t_j)|^k |W(t_{j+1}) - W(t_j)|$$

Let,  $M_\Pi = \max_j |W(t_{j+1}) - W(t_j)|$  for a given partition  $\Pi$ . Then,

$$\begin{aligned} \lim_{\|\Pi\| \rightarrow 0} \sum_{j=0}^{m-1} |W(t_{j+1}) - W(t_j)|^k |W(t_{j+1}) - W(t_j)| &\leq \lim_{\|\Pi\| \rightarrow 0} \sum_{j=0}^{m-1} |W(t_{j+1}) - W(t_j)|^k M_\Pi \\ &= \lim_{\|\Pi\| \rightarrow 0} M_\Pi \sum_{j=0}^{n-1} |W(t_{j+1}) - W(t_j)|^k \end{aligned}$$

Provided,  $|V_T(k, T)| = V_T(k, T)$  is not infinite,

$$\lim_{\|\Pi\| \rightarrow 0} M_\Pi \sum_{j=0}^{m-1} |W(t_{j+1}) - W(t_j)|^k = \left( \lim_{\|\Pi\| \rightarrow 0} M_\Pi \right) \left( \lim_{\|\Pi\| \rightarrow 0} \sum_{j=0}^{n-1} |W(t_{j+1}) - W(t_j)|^2 \right)$$

Since  $W(t)$  is continuous,  $|W(t_{j+1}) - W(t_j)| \rightarrow 0$  as  $\|\Pi\| \rightarrow 0$  since  $t_{j+1} - t_j \rightarrow 0$ . In particular, this means that  $M_\Pi \rightarrow 0$  as  $\|\Pi\| \rightarrow 0$ .



Thus,

$$0 \geq V_T(k+1, W) = \left( \lim_{\|\Pi\| \rightarrow 0} M_\Pi \right) \left( \lim_{\|\Pi\| \rightarrow 0} \sum_{j=0}^{m-1} |W(t_{j+1}) - W(t_j)|^k \right) \leq 0 \cdot N = 0$$

Recall  $V_T(2, W) = T < \infty$ . Then, by above,  $V_T(3, W) = 0$ .  $\square$

Suppose, for the sake of contradiction that  $V_T(1, W) \neq \infty$ . Clearly  $V_T(1, W) \geq 0$ , so  $V_T(1, W)$  is bounded above and below by finite constants. Then, by above,  $V_T(2, W) = 0$ , a contradiction (for  $T > 0$ ). This proves  $V_T(1, W) = \infty$ .  $\square$

**Exercise 7.4**

Define

$$X_t = \mu t + W_t \quad \tau_m := \inf\{t \geq 0 : X_t = m\}$$

Show that  $Z$  is a martingale where,

$$Z_t = \exp(\sigma X_t - (\sigma\mu + \sigma^2/2)t)$$

Assume  $\mu > 0$  and  $m \geq 0$ . Assume further that  $\tau_m < \infty$  with probability one and the stopped process  $Z_{t \wedge \tau_m}$  is a martingale. Find the Laplace transform  $\mathbb{E}e^{-\alpha\tau_m}$ .

**Solution**

Let  $0 \leq s \leq t$ . Rewrite,

$$\mathbb{E}[Z_t | \mathcal{F}_s] = \mathbb{E}\left[e^{\sigma X_t - (\sigma\mu + \sigma^2/2)t} | \mathcal{F}_s\right] = \mathbb{E}\left[e^{\sigma(\mu t + W_t) - (\sigma\mu + \sigma^2/2)t} | \mathcal{F}_s\right] = \mathbb{E}\left[e^{\sigma W_t - (\sigma^2/2)t} | \mathcal{F}_s\right]$$

Now, pulling out what is known,

$$\mathbb{E}\left[e^{\sigma W_t - (\sigma^2/2)t} | \mathcal{F}_s\right] = \mathbb{E}\left[e^{\sigma(W_t - W_s) + \sigma W_s - (\sigma^2/2)t} | \mathcal{F}_s\right] = e^{\sigma W_s - (\sigma^2/2)t} \mathbb{E}\left[e^{\sigma(W_t - W_s)} | \mathcal{F}_s\right]$$

By the property of independent increments,

$$e^{\sigma W_s - (\sigma^2/2)t} \mathbb{E}\left[e^{\sigma(W_t - W_s)} | \mathcal{F}_s\right] = e^{\sigma W_s - (\sigma^2/2)t} \mathbb{E}\left[e^{\sigma(W_t - W_s)}\right] = e^{\sigma W_s - (\sigma^2/2)t} e^{\sigma^2(t-s)/2}$$

Finally,

$$e^{\sigma W_s - (\sigma^2/2)t} e^{\sigma^2(t-s)/2} = e^{\sigma W_s - (\sigma^2/2)s} = e^{\sigma(\mu s + W_s) - (\sigma\mu + \sigma^2/2)s} = e^{\sigma X_s - (\sigma\mu + \sigma^2/2)s}$$

This proves  $Z_t$  is a martingale. □

Define  $s = \min\{t, \tau_m\}$ . Fix  $m \geq 0$  and define,

$$Z^{(m)} = \left(Z_t^{(m)}\right)_{t \geq 0}, \quad Z_t^{(m)} = Z_s$$

Then, using the fact that  $Z_t$  is a martingale we have,

$$1 = Z_0^{(m)} = \mathbb{E}\left[Z_t^{(m)}\right] = \mathbb{E}\left[e^{\sigma X_s - (\sigma\mu + \sigma^2/2)s}\right]$$

If  $\tau_m = \infty$  then  $X_t < m$  for all  $t$ . Thus, since  $\sigma \geq 0, \mu > 0$ ,

$$e^{\sigma X_t - (\sigma\mu + \sigma^2/2)t} \leq e^{\sigma m - (\sigma\mu + \sigma^2/2)t} < \infty$$

Therefore, since  $\mathbb{P}(\tau_m < \infty) = 0$ ,

$$\begin{aligned} \mathbb{E} \left[ e^{\sigma X_s - (\sigma\mu + \sigma^2/2)s} \right] &= \mathbb{E} \left[ \mathbb{1}_{\{\tau_m = \infty\}} \left( e^{\sigma X_s - (\sigma\mu + \sigma^2/2)s} \right) + \mathbb{1}_{\{\tau_m < \infty\}} \left( e^{\sigma X_s - (\sigma\mu + \sigma^2/2)s} \right) \right] \\ &= \mathbb{E} \left[ \mathbb{1}_{\{\tau_m = \infty\}} \left( e^{\sigma X_t - (\sigma\mu + \sigma^2/2)t} \right) \right] + \mathbb{E} \left[ \mathbb{1}_{\{\tau_m < \infty\}} \left( e^{\sigma X_{\tau_m} - (\sigma\mu + \sigma^2/2)\tau_m} \right) \right] \\ &= 0 + \mathbb{E} \left[ \mathbb{1}_{\{\tau_m < \infty\}} \left( e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} \right) \right] \end{aligned}$$

Similarly, since  $\sigma \geq 0, \mu > 0$ ,  $e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} < \infty$ . Therefore,

$$\begin{aligned} \mathbb{E} \left[ \mathbb{1}_{\{\tau_m < \infty\}} \left( e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} \right) \right] &= \mathbb{E} \left[ \mathbb{1}_{\{\tau_m = \infty\}} \left( e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} \right) \right] + \mathbb{E} \left[ \mathbb{1}_{\{\tau_m < \infty\}} \left( e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} \right) \right] \\ &= \mathbb{E} \left[ \mathbb{1}_{\{\tau_m = \infty\}} \left( e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} \right) + \mathbb{1}_{\{\tau_m < \infty\}} \left( e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} \right) \right] \\ &= \mathbb{E} \left[ e^{\sigma m - (\sigma\mu + \sigma^2/2)\tau_m} \right] \end{aligned}$$

Then, setting  $\alpha = (\sigma\mu + \sigma^2/2)$ ,

$$e^{-\sigma m} = \mathbb{E} \left[ e^{-(\sigma\mu + \sigma^2/2)\tau_m} \right] = \mathbb{E} \left[ e^{-\alpha\tau_m} \right]$$

We solve the equation,  $\alpha = (\sigma\mu + \sigma^2/2)$  for  $\sigma$  using the quadratic equation, yielding,

$$\sigma = -\mu \pm \sqrt{\mu^2 + 2\alpha}$$

However,  $\sigma, \alpha \geq 0$  so we must take  $\sigma = -\mu + \sqrt{\mu^2 + 2\alpha}$ . Thus,

$$\mathbb{E} \left[ e^{-\alpha\tau_m} \right] = e^{(\mu - \sqrt{\mu^2 + 2\alpha})m}$$

**Exercise 8.1**

Compute  $d(W_t^4)$ . Write  $W_T^4$  as an integral with respect to  $W$  plus an integral with respect to  $t$ . Use this representation of  $W_T^4$  to show that  $\mathbb{E}W_T^4 = 3T^2$ . Compute  $\mathbb{E}W_T^6$  using the same technique.

**Solution**

Write  $f(x) = x^4$  so that  $f(W_t) = W_t^4$ . Then,  $f'(x) = 4x^3$  and  $f''(x) = 12x^2$ . Therefore, Itô's formula gives,

$$dW_t^4 = f'(W_t)dW_t + \frac{1}{2}f''(W_t)d[W, W]_t = 4W_t^3dW_t + \frac{12}{2}W_t^2d[W, W]_t$$

Thus, writing  $d[W, W]_t = dt$  we have,

$$dW_t^4 = 4W_t^3dW_t + 6W_t^2dt$$

Thus, since  $W_0 = 0$ ,

$$W_T^4 = W_T^4 - W_0^4 = 4 \int_0^T W_t^3dW_t + 6 \int_0^T W_t^2dt$$

Recall Itô integrals are martingales so that,

$$\mathbb{E} \left[ \int_0^T W_t^3dW_t \right] = 0$$

Note also that since  $\mathbb{E}[W_t^2] = t$ ,

$$\mathbb{E} \left[ \int_0^T W_t^2dt \right] = \int_0^T \mathbb{E}[W_t^2] dt = \int_0^T tdt = \frac{T^2}{2}$$

Therefore,

$$\mathbb{E}[W_T^4] = 4\mathbb{E} \left[ \int_0^T W_t^3dW_t \right] + 6\mathbb{E} \left[ \int_0^T W_t^2dt \right] = 6\frac{T^2}{2} = 3T^2$$

Similarly, we have,

$$W_T^6 = 6 \int_0^T W_t^5dW_t + \frac{6 \cdot 5}{2} \int_0^T W_t^4dt$$

Therefore, since  $\mathbb{E} [W_t^4] = 3t^2$ ,

$$\mathbb{E} [W_T^6] = 6\mathbb{E} \left[ \int_0^T W_t^5 dW_t \right] + 15\mathbb{E} \left[ \int_0^T W_t^4 dt \right] = 15 \int_0^T \mathbb{E} [W_t^4] dt = 15 \int_0^T 3t^2 dt = 15T^3$$

**Exercise 8.2**

Find an explicit expression for  $Y_T$  where,

$$dY_t = rdt + \alpha Y_t dW_t$$

Hint: Multiply the above equation by  $F_t := \exp(-\alpha W_t + \frac{1}{2}\alpha^2 t)$ .

**Solution**

Let  $f(x, y) = \exp(-\alpha x + \frac{1}{2}\alpha^2 y)$  so that,

$$f_x(W_t, t) = -\alpha F_t \quad f_y(W_t, t) = \frac{\alpha^2}{2} F_t \quad f_{xx}(W_t, t) = \alpha^2 F_t$$

Then  $F_t = f(W_t, t)$ , so by Itô's formula and the heuristic  $(dW_t)^2 = dt, (dt)^2 = dt dW_t = 0$ ,

$$\begin{aligned} dF_t &= df(W_t, t) = f_y(W_t, t)dt + f_x(W_t, t)dW_t + \frac{1}{2}f_{xx}(W_t, t)(dW_t)^2 \\ &= \frac{\alpha^2}{2}F_t dt - \alpha F_t dW_t + \frac{\alpha^2}{2}F_t dt \\ &= \alpha^2 F_t dt - \alpha F_t dW_t \end{aligned}$$

Using our heuristics we have,

$$d[F, Y]_t = (dF_t)(dY_t) = (\alpha^2 F_t dt - \alpha F_t dW_t)(rdt + \alpha Y_t dW_t) = -\alpha^2 F_t Y_t (dW_t)^2 = -\alpha^2 F_t Y_t dt$$

By the product rule we have,

$$\begin{aligned} d(F_t Y_t) &= F_t dY_t + Y_t dF_t + d[F, Y]_t \\ &= F_t(rdt + \alpha Y_t dW_t) + Y_t(\alpha^2 F_t dt - \alpha F_t dW_t) - \alpha^2 F_t Y_t dt \\ &= rF_t dt \end{aligned}$$

In integral form,

$$F_t Y_t - F_0 Y_0 = \int_0^t r F_s ds = \int_0^t r e^{-\alpha W_s + \frac{1}{2}\alpha^2 s} ds$$

We can add  $F_0 Y_0 = Y_0$  and divide by  $F_t$  yielding,

$$Y_t = Y_0 + r e^{\alpha W_t - \frac{1}{2}\alpha^2 t} \int_0^t e^{-\alpha W_s + \frac{1}{2}\alpha^2 s} ds$$

**Exercise 8.3**

Suppose  $X$ ,  $\Delta$ , and  $\Pi$  are given by,

$$dX_t = \sigma X_t dW_t, \quad \Delta_t = \frac{\partial f}{\partial x}(t, X_t), \quad \Pi_t = X_t \Delta_t$$

where  $f$  is some smooth function. Show that if  $f$  satisfies,

$$\left( \frac{\partial}{\partial t} + \frac{1}{2} \sigma^2 x^2 \frac{\partial^2}{\partial x^2} \right) f(t, x) = 0$$

for all  $(t, x)$ , then  $\Pi$  is a martingale with respect to a filtration  $\mathcal{F}_t$  for  $W$ .

**Solution**

We have,

$$\frac{\partial}{\partial x} \left( \frac{\partial}{\partial t} + \frac{1}{2} \sigma^2 x^2 \frac{\partial^2}{\partial x^2} \right) = \frac{\partial^2}{\partial x \partial t} + \frac{1}{2} \sigma^2 \left[ x^2 \frac{\partial^3}{\partial x^3} + 2x \frac{\partial^2}{\partial x^2} \right]$$

Thus, using the condition for  $f$  we have,

$$\frac{\partial^2 f}{\partial x \partial t} + \frac{1}{2} \sigma^2 X_t^2 \frac{\partial^3 f}{\partial x^3} = -\sigma^2 X_t \frac{\partial^2 f}{\partial x^2}$$

Using our heuristics we have,

$$d[X, X] = \sigma^2 X_t^2 (dW_t)^2 = \sigma^2 X_t^2 dt$$

Similarly,

$$d[X, t] = d[t, X] = d[t, t] = 0$$

Therefore, by Itô's formula,

$$\begin{aligned} d\Delta_t &= \frac{\partial^2 f}{\partial x \partial t}(t, X_t) dt + \frac{\partial^2 f}{\partial x^2}(t, X_t) dX_t + \frac{1}{2} d[X, X] \\ &= \frac{\partial^2 f}{\partial x \partial t}(t, X_t) dt + \sigma X_t \frac{\partial^2 f}{\partial x^2}(t, X_t) dW_t + \frac{1}{2} \sigma^2 X_t^2 \frac{\partial^3 f}{\partial x^3}(t, X_t) dt \\ &= -\sigma^2 X_t \frac{\partial^2 f}{\partial x^2}(t, X_t) dt + \sigma X_t \frac{\partial^2 f}{\partial x^2}(t, X_t) dW_t \end{aligned}$$

Therefore,

$$d[X, \Delta]_t = (dX_t)(d\Delta_t) = \sigma^2 X_t^2 \frac{\partial^2 f}{\partial x^2}(t, X_t) (dW_t)^2 = \sigma^2 X_t^2 \frac{\partial^2 f}{\partial x^2}(t, X_t) dt$$

Finally, we have,

$$\begin{aligned} d\Pi_t &= d(X_t \Delta_t) = X_t d\Delta_t + \Delta_t dX_t + d[X, \Delta]_t \\ &= X_t \left( -\sigma^2 X_t \frac{\partial^2 f}{\partial x^2}(t, X_t) dt + \sigma X_t \frac{\partial^2 f}{\partial x^2}(t, X_t) dW_t \right) + \sigma X_t \frac{\partial f}{\partial x}(t, X_t) dW_t + \sigma^2 X_t^2 \frac{\partial^2 f}{\partial x^2} dt \\ &= \sigma X_t \left( X_t \frac{\partial^2 f}{\partial x^2}(t, X_t) + \frac{\partial f}{\partial x}(t, X_t) \right) dW_t \end{aligned}$$

Since there is no  $dt$  dependence this is an Itô integral and therefore a martingale with respect to a filtration for  $W$ . (there are probably some technical assumptions we need about  $X$  and  $f$ , but in class we never dealt with these)  $\square$



**Exercise 8.4**

Suppose  $X$  is given by,

$$dX_t = \mu(t, X_t)dt + \sigma(t, X_t)dW_t$$

For any smooth function  $f$  define,

$$M_t^f := f(t, X_t) - f(0, X_0) - \int_0^t \left( \frac{\partial}{\partial s} + \mu(s, X_s) \frac{\partial}{\partial x} + \frac{1}{2} \sigma^2(s, X_s) \frac{\partial^2}{\partial x^2} \right) f(s, X_s) ds$$

Show that  $M^f$  is a martingale with respect to a filtration  $\mathcal{F}_t$  for  $W$ .

**Solution**

We first compute,

$$d[X, X]_t = (dX_t)(dX_t) = \sigma^2(t, X_t)(dW_t)^2 = \sigma^2(t, X_t)dt$$

We then have,

$$\begin{aligned} df(t, X_t) &= \frac{\partial f}{\partial t}(t, X_t)dt + \frac{\partial f}{\partial x}(t, X_t)dX_t + \frac{1}{2} \frac{\partial^2 f}{\partial x^2} d[X, X]_t \\ &= \frac{\partial f}{\partial t}(t, X_t)dt + \frac{\partial f}{\partial x}(t, X_t)[\mu(t, X_t)dt + \sigma(t, X_t)dW_t] + \frac{1}{2} \sigma^2(t, X_t) \frac{\partial^2 f}{\partial x^2} dt \\ &= \left( \frac{\partial}{\partial t} + \mu(t, X_t) \frac{\partial}{\partial x} + \frac{1}{2} \sigma^2(t, X_t) \frac{\partial^2}{\partial x^2} \right) f(t, X_t)dt + \sigma(t, X_t) \frac{\partial f}{\partial x} dW_t \end{aligned}$$

Finally, since  $f(0, X_0)$  is a constant,

$$\begin{aligned} dM_t^f &= df(t, X_t) - \left( \frac{\partial}{\partial t} + \mu(t, X_t) \frac{\partial}{\partial x} + \frac{1}{2} \sigma^2(t, X_t) \frac{\partial^2}{\partial x^2} \right) f(t, X_t)dt \\ &= \sigma(t, X_t) \frac{\partial f}{\partial x} dW_t \end{aligned}$$

Since there is no  $dt$  dependence this is an Itô integral and therefore a martingale with respect to a filtration for  $W$ .  $\square$

**Exercise 9.1****Solution**

**Exercise 9.2**

Let  $X$  be a solution to the following SDE

$$dX_t = \kappa(\theta - X_t)dt + \delta\sqrt{X_t}dW_t$$

Define

$$u(t, x) = \mathbb{E} \left[ \exp \left( - \int_t^T X_s ds \right) \middle| X_t = x \right]$$

Derive a PDE for the function  $u$ . To solve the PDE for  $u$ , try a solution of the form

$$u(t, x) = \exp(-xA(t) - B(t)),$$

where  $A$  and  $B$  are deterministic functions of  $t$ . Show that  $A$  and  $B$  must satisfy a pair of coupled ODEs (with appropriate terminal conditions at time  $T$ ). Bonus question: solve the ODEs (it may be helpful to note that one of the ODEs is a Riccati equation).

**Solution (direct)**

First observe that  $u(t, X_t)$  is not a martingale as,

$$\begin{aligned} \mathbb{E}[u(t, X_t) | \mathcal{F}_s] &= \mathbb{E} \left[ \mathbb{E} \left[ \exp \left( - \int_t^T X_z dz \right) \middle| \mathcal{F}_t \right] \middle| \mathcal{F}_s \right] \\ &= \mathbb{E} \left[ \exp \left( - \int_t^T X_z dz \right) \middle| \mathcal{F}_s \right] \\ &\neq \mathbb{E} \left[ \exp \left( - \int_s^T X_z dz \right) \middle| \mathcal{F}_s \right] \\ &= u(s, X_s) \end{aligned}$$

Define,

$$M_t = \exp \left( - \int_0^t X_z dz \right) u(t, X_t) = \mathbb{E} \left[ \exp \left( - \int_0^T X_z dz \right) \middle| \mathcal{F}_t \right]$$

where we have used the fact that  $\exp(-\int_0^t X_z dz) \in \mathcal{F}_t$ .

Clearly,

$$\mathbb{E}[M_t | \mathcal{F}_s] = \mathbb{E} \left[ \mathbb{E} \left[ \exp \left( - \int_0^T X_z dz \right) \middle| \mathcal{F}_t \right] \middle| \mathcal{F}_s \right] = \mathbb{E} \left[ \exp \left( - \int_0^T X_z dz \right) \middle| \mathcal{F}_s \right] = M_s$$

Therefore  $M_t$  is a martingale.

Note that,

$$\begin{aligned} du(t, X_t) &= \partial_t u(t, X_t)dt + \partial_x u(t, X_t)dX_t + \frac{1}{2}\partial_x^2 u(t, X_t)d[X, X]_t \\ &= \left( \partial_t + \mu(t, X_t)\partial_x + \frac{1}{2}\sigma^2(t, X_t)\partial_x^2 \right) u(t, X_t)dt + \sigma(t, X_t)\partial_x u(t, X_t)dW_t \end{aligned}$$

Write  $v(t, X_t) = \exp(-\int_0^t X_z dz)$ . This does not depend on  $X_t$  so,

$$\begin{aligned} dv(t, X_t) &= \partial_t v(t, X_t)dt + \partial_x v(t, X_t)dX_t + \frac{1}{2}\partial_x^2 v(t, X_t)d[X, X]_t \\ &= -X_t v(t, X_t)dt \end{aligned}$$

We suppress the arguments to  $u, v, \mu, \sigma$  and compute,

$$\begin{aligned} dM_t &= u(t, X_t)dv(t, X_t) + v(t, X_t)du(t, X_t) + d[u, v]_t \\ &= u(-X_t v)dt + v \left( \partial_t + \mu\partial_x + \frac{1}{2}\sigma^2\partial_x^2 \right) udt + (\cdots) dW_t \\ &= \left( \partial_t + \frac{1}{2}\sigma^2\partial_x^2 + \mu\partial_x - X_t \right) udt + (\cdots) dW_t \end{aligned}$$

Since  $M_t$  is a martingale, the  $dt$  term must be zero. Moreover,  $v$  is always positive. Therefore,

$$\left[ \left( \partial_t + \frac{1}{2}\sigma^2(t, x)\partial_x^2 + \mu(t, x)\partial_x - x \right) u(t, x) \right]_{t=t, x=X_t} = 0$$

The boundary condition is obtained by,

$$u(T, X_T) = \mathbb{E} \left[ \exp \left( - \int_T^T X_z dz \right) \middle| \mathcal{F}_T \right] = 1$$

The rest of the solution is included below.

### Solution

With  $\gamma(u, x) = x$ ,  $\phi(x) = 1$ ,  $g(u, x) = 0$  this is a subcase of an example in the notes. We then know  $u(t, x)$  solves,

$$(\partial_t + \mathcal{A})u + g = 0, \quad u(T, \cdot) = \phi, \quad \mathcal{A} = \frac{1}{2}\sigma^2\partial_x^2 + \mu\partial_x - \gamma = 0$$

Assume  $u$  has the form,

$$u(t, x) = \exp(-xA(t) - B(t))$$

First compute,

$$\partial_t u = (-xA' - B')u \quad \partial_x u = -Au \quad \partial_x^2 u = A^2 u$$

This gives,

$$\begin{aligned} 0 &= \left[ \partial_t + \frac{1}{2} \delta^2 x \partial_x^2 + \kappa(\theta - x) \partial_x - x \right] u \\ &= \left[ -xA' - B' + \frac{1}{2} \delta^2 x A^2 + \kappa(\theta - x)(-A) - x \right] u \\ &= \left[ \left( -A' + \frac{1}{2} \delta^2 A^2 + \kappa A - 1 \right) x + (-B' - \kappa \theta A) \right] u \end{aligned}$$

Observe  $u(t, x) > 0$  for all  $t, x$ . Therefore we require the bracketed term above to be zero for all  $x, t$ . Setting the coefficients of the  $x$  terms and constant terms to zero gives a coupled pair of ODEs,

$$\begin{cases} -A'(t) + \frac{1}{2} \delta^2 A^2(t) + \kappa A(t) - 1 = 0 \\ -B'(t) - \kappa \theta A(t) = 0 \end{cases}$$

We have,

$$1 = \varphi(x) = u(T, x) = \exp(-xA(T) - B(T))$$

This gives terminal condition,

$$A(T) = 0 \quad B(T) = 0$$

We solve this in Mathematica without boundary conditions using,

```
DSolve[{-D[A[t],t]+1/2 \[Delta]^2 A[t]^2+\[Kappa] A[t] - 1 ==0 , -
D[B[t],t]-\[Kappa] \[Theta] A[t]==0},{A,B},t]
```

This gives solution,

$$A(t) = \frac{\sqrt{-2\delta^2 - \kappa^2} \tan\left(\frac{1}{2}\left(2c_1\sqrt{-2\delta^2 - \kappa^2} + t\sqrt{-2\delta^2 - \kappa^2}\right)\right) - \kappa}{\delta^2}$$

$$B(t) = \frac{\theta\kappa\left(2\log\left(\cos\left(c_1\sqrt{-2\delta^2 - \kappa^2} + \frac{1}{2}t\sqrt{-2\delta^2 - \kappa^2}\right)\right) + \kappa t\right)}{\delta^2} + c_2$$

where,

$$c_1 = \frac{1}{2\sqrt{-2\delta^2 - \kappa^2}} \left[ 2 \arctan\left(\frac{\kappa}{\sqrt{-2\delta^2 - \kappa^2}}\right) - T\sqrt{-2\delta^2 - \kappa^2} \right]$$

$$c_2 = -\frac{\theta\kappa\left(2\log\left(\cos\left(c_1\sqrt{-2\delta^2 - \kappa^2} + \frac{1}{2}T\sqrt{-2\delta^2 - \kappa^2}\right)\right) + \kappa T\right)}{\delta^2}$$

**Exercise 9.3**

For  $i = 1, 2, \dots, d$  let  $X^{(i)}$  satisfy,

$$dX_t^{(i)} = -\frac{b}{2}X_t^{(i)}dt + \frac{1}{2}\sigma dW_t^{(i)}$$

where  $(W_t^{(i)})_{i=1}^d$  are independent Brownian motions. Define

$$R_t := \sum_{i=1}^d \left(X_t^{(i)}\right)^2, \quad B_t := \sum_{i=1}^d \int_0^t \frac{1}{\sqrt{R_s}} X_s^{(i)} dW_s^{(i)}$$

Show that  $B$  is a Brownian motion. Derive an SDE for  $R$  that involves only  $dt$  and  $dB_t$  terms (i.e., no  $dW_t^{(i)}$  terms should appear).

**Solution**

We use the Lévy characterization of Brownian motion. In particular, we must show  $B$  is a martingale,  $B$  has continuous sample paths, and  $B_0 = 0$  with  $[B, B]_t = t$  for all  $t \geq 0$ .

Write,

$$dB_t = d \left[ \sum_{i=1}^d \int_0^t \frac{1}{\sqrt{R_s}} X_s^{(i)} dW_s^{(i)} \right] = \sum_{i=1}^d \frac{1}{\sqrt{R_t}} X_t^{(i)} dW_t^{(i)}$$

As  $B_t$  is an Itô integral it is a martingale with respect to a filtration  $\mathbb{F} = (\mathcal{F}_t)_{t \geq 0}$  for  $W_t^{(i)}$ .

Similarly,  $B_t$  has continuous sample paths as  $W_t^{(i)}$  have continuous sample paths.

Clearly  $B_0 = 0$  as  $W_0^{(i)} = 0$ .

Now,

$$\begin{aligned} (dB_t)(dB_t) &= \frac{1}{R_t} \sum_{i=1}^d \sum_{j=1}^d X_t^{(i)} X_t^{(j)} dW_t^{(i)} dW_t^{(j)} \\ &= \frac{1}{R_t} \left( \sum_{j=1}^d \left( X_t^{(j)} dW_t^{(j)} \right)^2 + 2 \sum_{i=1}^d \sum_{j=1}^i X_t^{(i)} X_t^{(j)} dW_t^{(i)} dW_t^{(j)} \right) \end{aligned}$$

Using the heuristic,  $dW_t^{(i)}dW_t^{(j)} = \delta_{ij}dt$  and the definition of  $R_t$  we have,

$$d[B, B]_t = \frac{1}{R_t} \sum_{i=1}^d \left(X_t^{(i)}\right)^2 dt = dt$$

Therefore,  $[B, B]_t = t$ .

This proves  $B$  is a Brownian motion. □

Compute, using Itô's formula,

$$dR_t = d \left[ \sum_{i=1}^d \left(X_t^{(i)}\right)^2 \right] = \sum_{i=1}^d 2X_t^{(i)} dX_t^{(i)} + \frac{1}{2} 2d[X^{(i)}, X^{(i)}]_t = \sum_{i=1}^d 2X_t^{(i)} dX_t^{(i)} + d[X^{(i)}, X^{(i)}]_t$$

Using our heuristics we have,

$$d[X^{(i)}, X^{(i)}]_t = \left(dX_t^{(i)}\right) \left(dX_t^{(i)}\right) = \left(-\frac{b}{2}X_t^{(i)}dt + \frac{1}{2}\sigma dW_t^{(i)}\right)^2 = \frac{\sigma^2}{4}dt$$

Now,

$$\begin{aligned} \sum_{i=1}^d 2X_t^{(i)} dX_t^{(i)} + d[X^{(i)}, X^{(i)}]_t &= \sum_{i=1}^d 2X_t^{(i)} \left(-\frac{b}{2}X_t^{(i)}dt + \frac{1}{2}\sigma dW_t^{(i)}\right) + \frac{\sigma^2}{4}dt \\ &= \sum_{i=1}^d \left(\frac{\sigma^2}{4} - b \left(X_t^{(i)}\right)^2\right) dt + \sigma \sqrt{R_t} \frac{1}{\sqrt{R_t}} X_t^{(i)} dW_t^{(i)} \end{aligned}$$

Therefore, simplifying slightly we have,

$$dR_t = (d\sigma^2/4 - bR_t)dt + \sigma\sqrt{R_t}dB_t$$



**Exercise 9.4****Solution**

**Exercise 9.5**

Consider a diffusion  $X = (X_t)_{t \geq 0}$  that lives on a finite interval  $(l, r)$ ,  $0 < l < r < \infty$  and satisfies the SDE

$$dX_t = \mu X_t dt + \sigma X_t dW_t$$

One can easily check that the endpoints  $l$  and  $r$  are regular (you do not have to prove it here). Assume both endpoints are killing. Find the transition density  $\Gamma(t, x; T, y)$  of  $X$ .

**Solution**

We have,  $\Gamma(\cdot, \cdot; T, y)$  satisfies,

$$(\partial_t + \mathcal{A}(t))\Gamma(\cdot, t; T, y) = 0 \quad \Gamma(T, \cdot; T, y) = \delta_y$$

where the infinitesimal generator  $\mathcal{A}$  is,

$$\mathcal{A} = \mu x \partial_x + \frac{1}{2} \sigma^2 x^2 \partial_x^2$$

We seek a spectral representation for  $\mathcal{A}$ . That is, a basis  $\{\Psi_n\}_{n \geq 0}$  for such that  $\mathcal{A}\Psi_n = \lambda_n \Psi_n$ .

Since the endpoints are killing we also require,

$$\Psi_n(l) = 0, \quad \Psi_n(r) = 0$$

We make a change of variables. Let  $z = \log(x)$ . Then,

$$\partial_x = \frac{1}{x} \partial_z, \quad \partial_x^2 = -\frac{1}{x^2} \partial_z + \frac{1}{x} \partial_z^2$$

Then, in terms of  $z$  we have generator,

$$\mathcal{A}_z = \left( \mu - \frac{\sigma^2}{2} \right) \partial_z + \frac{1}{2} \sigma^2 \partial_z^2$$

This equation is very similar to a damped harmonic oscillator. We therefore guess that the eigenfunctions have the form,

$$\psi_n(z) = \exp(\gamma_n z) \left[ A \sin \left( \frac{n\pi(z - \log(l))}{\log(r) - \log(l)} \right) + B \cos \left( \frac{n\pi(z - \log(l))}{\log(r) - \log(l)} \right) \right]$$

In order to satisfy the boundary conditions listed above we need  $B = 0$ . The constant  $A$  will be determined by the normalization of  $\psi_n$ , so we will leave it off until the end.

For convenience, write,

$$\psi = \psi_n, \quad \gamma = \gamma_n, \quad k = \frac{n\pi}{\log(l/r)}, \quad \cos(z') = \cos(k(z - \log l))$$

We then have,

$$\begin{aligned} \partial_z \psi(z) &= \gamma \psi + \exp(\gamma z) k \cos(z') \\ \partial_z^2 \psi(z) &= \gamma^2 \psi + \gamma \exp(\gamma z) k \cos(z') + \gamma \exp(\gamma z) k \cos(z') - k^2 \psi \\ &= \gamma^2 \psi + 2\gamma \exp(\gamma z) k \cos(z') - k^2 \psi \end{aligned}$$

We seek  $\gamma$  such that  $\mathcal{A}_z \psi = \lambda \psi$  for some constant  $\lambda$ . That is, in our expression of  $\mathcal{A}_z \psi$  we require the terms not containing a  $\psi$  be zero. Thus,

$$\begin{aligned} 0 &= \left( \mu - \frac{\sigma^2}{2} \right) \exp(\gamma z) k \cos(z') + \left( \frac{\sigma^2}{2} \right) 2\gamma \exp(\gamma z) k \cos(z') \\ &= \left[ \left( \mu - \frac{\sigma^2}{2} \right) + \sigma^2 \gamma \right] \exp(\gamma z) \cos(z') \end{aligned}$$

Suppose  $k \neq 0$  (i.e. that the solution is non-trivial). Since  $\exp(\gamma z)$  and  $\cos(z') \neq 0$  we have,

$$0 = \left( \mu - \frac{\sigma^2}{2} \right) + \sigma^2 \gamma$$

Solving for  $\gamma$  we have,

$$\gamma = \frac{1}{2} - \frac{\mu}{\sigma^2}$$

The eigenvalues are,

$$\lambda_n = \left( \mu - \frac{\sigma^2}{2} \right) \gamma + \left( \frac{\sigma^2}{2} \right) (\gamma^2 - k^2) = -\frac{\sigma^2}{2} [k^2 + \gamma^2]$$

Transforming back to  $x$  we have,  $\hat{\Psi}_n(x) = \psi_n(\log(x))$  satisfies,

$$\mathcal{A} \hat{\Psi}_n(x) = \lambda_n \hat{\Psi}_n(x), \quad \mathcal{A} = \mu x \partial_x + \frac{1}{2} \sigma^2 x^2 \partial_x^2$$

Define,

$$m(y) = \frac{2}{\sigma^2 y^2} \exp \left( \int dy \frac{2\mu y}{\sigma^2 y^2} \right) = \frac{2}{\sigma^2 y^2} \exp \left( \frac{2\mu}{\sigma^2} \log(y) \right) = \frac{2}{\sigma^2} y^{2\mu/\sigma^2 - 2} = \frac{2}{\sigma^2} y^{-2\gamma - 1}$$

It is clear that the  $\hat{\Psi}_n$  are orthogonal (properties of sines). We compute,

$$\langle \hat{\Psi}_n(x), \hat{\Psi}_n(x) \rangle_m = \int_l^r \Psi_n(x)^2 m(x) dx = \log(r/l)/\sigma^2$$

We then satisfy  $\langle \Psi_k, \Psi_l \rangle_m = \delta_{kl}$  by defining,

$$\Psi_n(x) = \frac{\hat{\Psi}_n(x)}{\sqrt{\langle \hat{\Psi}_n(x), \hat{\Psi}_n(x) \rangle_m}}$$

Explicitly,

$$\Psi_n(x) = \frac{\sigma}{\sqrt{\log(r/l)}} x^\gamma \sin(k(z - \log l)) = \frac{\sigma}{\sqrt{\log(r/l)}} x^{1/2 - \mu/\sigma^2} \sin \left( n\pi \frac{\log(x/l)}{\log(r/l)} \right)$$

Finally,

$$\Gamma(t, x; T, y) = m(y) \sum_n \exp((T - t)\lambda_n) \Psi_n(x) \Psi_n(y)$$

Explicitly,

$$\Gamma(t, x; T, y) = \frac{2}{\log(r/l)} \left( \frac{x}{y} \right)^{1/2 - \mu/\sigma^2} y^{-1} \sum_n \exp((T - t)\lambda_n) \sin \left( n\pi \frac{\log(x/l)}{\log(r/l)} \right) \sin \left( n\pi \frac{\log(y/l)}{\log(r/l)} \right)$$

Since the  $\Psi_n$  are normalized then  $\Gamma$  is normalized.

We verify in Mathematica that  $\Gamma$  satisfies both the KFE and KBE.

**Exercise 9.6**

Consider a two-dimensional diffusion processes  $X = (X_t)_{t \geq 0}$  and  $Y = (Y_t)_{t \geq 0}$  that satisfy the SDEs

$$dX_t = dW_t^1 \quad dY_t = dW_t^2$$

where  $W_t^1$  and  $W_t^2$  are two independent Brownian motions. Define a function  $u$  as follows

$$u(x, y) = \mathbb{E}[\phi(X_\tau) | X_t = x, Y_t = y], \quad \tau = \inf\{s \geq t : Y_s = a\}$$

1. State a PDE and boundary conditions satisfied by the function  $u$ .
2. Let us define the Fourier transform and inverse Fourier transform, respectively, as follows

$$\text{Fourier Transform:} \quad \hat{f}(\omega) := \int e^{-i\omega x} f(x) dx$$

$$\text{Inverse Transform:} \quad f(x) := \frac{1}{2\pi} \int e^{i\omega x} \hat{f}(\omega) d\omega$$

Use Fourier transforms and a conditioning argument to derive an expression for  $u(x, y)$  as an inverse Fourier transform. Use this result to derive an explicit form for  $\mathbb{P}(X_\tau \in dz | X_t = x, Y_t = y)$  (i.e., an expression involving no integrals).

3. Show the expression you derived in part 2 for  $u(x, y)$  satisfies the PDE and BCs you stated in part 1.

**Solution**

1. Since there are no  $dt$  terms in either Brownian motion, and since the coefficient in both of the  $dW_t$  term is 1 we have, generator,

$$\mathcal{A} = \frac{1}{2} \partial_x^2 + \frac{1}{2} \partial_y^2$$

The PDE satisfied by  $u$  is,

$$\mathcal{A}u = \left( \frac{1}{2} \partial_x^2 + \frac{1}{2} \partial_y^2 \right) u = 0 \quad \Longleftrightarrow \quad (\partial_x^2 + \partial_y^2) u = 0$$

If  $y = a$  then  $\tau = t$  so  $X_\tau = x$ . We therefore have boundary condition,

$$u(x, a) = \phi(x)$$

2. Given starting position  $(x, y)$  at time  $t$ , and time  $\tau$ , from the notes we know  $X_\tau$  is normally distributed with mean  $x$  and variance  $\tau - t$  by the independent increments property of Brownian motion. We know the characteristic function of a normally distributed random variable with distribution  $\mathcal{N}(\mu, \sigma^2)$  is  $e^{i\omega\mu - \sigma^2\omega^2/2}$ . Therefore,

$$\mathbb{E} \left[ e^{i\omega X_\tau} \middle| \tau, X_t = x, Y_t = y \right] = e^{i\omega x - (\tau-t)\omega^2/2}$$

Thus, using iterated conditioning,

$$\begin{aligned} \mathbb{E} \left[ e^{i\omega X_\tau} \middle| X_t = x, Y_t = y \right] &= \mathbb{E} \left[ \mathbb{E} [e^{i\omega X_\tau} | \tau, X_t = x, Y_t = y] \middle| X_t = x, Y_t = y \right] \\ &= \mathbb{E} \left[ e^{i\omega x - (\tau-t)\omega^2/2} \middle| X_t = x, Y_t = y \right] \\ &= e^{i\omega x} \mathbb{E} \left[ e^{-(\tau-t)\omega^2/2} \middle| X_t = x, Y_t = y \right] \end{aligned}$$

We have previously shown that the first hitting time of a Brownian motion  $\tau_m$  satisfies,

$$\mathbb{E} \left[ e^{-\lambda \tau_m} \right] = e^{-|m|\sqrt{2\lambda}}$$

where  $\tau_m = \inf\{t \geq 0 : W_t = m\}$  and  $W_0 = 0$ .

Since we start at position  $y$  at time  $t$  (rather than position 0 and time 0 as above), we know that,

$$\mathbb{E} \left[ e^{-(\omega^2/2)(\tau-t)} \middle| X_t = x, Y_t = y \right] = e^{-|a-y||\omega|}$$

Therefore,

$$\mathbb{E} \left[ e^{i\omega X_\tau} \middle| X_t = x, Y_t = y \right] = e^{-|a-y||\omega|}$$

Write,

$$\phi(x) = \frac{1}{2\pi} \int_{\mathbb{R}} e^{i\omega x} \hat{\phi}(\omega) d\omega$$

Then,

$$u(x, y) = \mathbb{E}[\phi(X_\tau) | X_t = x, Y_t = y] = \mathbb{E} \left[ \frac{1}{2\pi} \int_{\mathbb{R}} e^{i\omega X_\tau} \hat{\phi}(\omega) d\omega \middle| X_t = x, Y_t = y \right]$$

Now, bringing the expectation through the integral, and applying the above result,

$$\begin{aligned}\mathbb{E} \left[ \frac{1}{2\pi} \int_{\mathbb{R}} e^{i\omega X_\tau} \hat{\phi}(\omega) d\omega \middle| X_t = x, Y_t = y \right] &= \frac{1}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) \mathbb{E} [e^{i\omega X_\tau} | X_t = x, Y_t = y] d\omega \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) e^{-|a-y||\omega|} e^{i\omega x} d\omega\end{aligned}$$

First recall,  $\mathbb{E}[\phi(X)] = \int \phi(x) f_X(x) dx$  and  $\mathbb{P}(X \in dz) = f_X(z) dz$ . Then, taking  $\phi(x) = \mathbb{1}_{\{x \in dz\}}$  means  $\mathbb{E}[\phi(X)] = f_X(z) dz = \mathbb{P}(X \in dz)$ . Therefore,

$$u(x, y) = \mathbb{E}[\mathbb{1}_{\{X_\tau \in dz\}} | X_t = x, Y_t = y] = \mathbb{P}(X_\tau \in dz | X_t = x, Y_t = y)$$

In this case,

$$\hat{\phi}(\omega) = \int_{\mathbb{R}} e^{-i\omega x} \mathbb{1}_{\{x \in dz\}} dx = e^{-i\omega z} dz$$

Thus, computing this integral by splitting it at 0,

$$\begin{aligned}u(x, y) &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{-i\omega z} dz e^{-|a-y||\omega|} e^{i\omega x} d\omega \\ &= \frac{1}{2\pi} \left[ \frac{2|a-y|}{(a-y)^2 + (x-z)^2} \right] dz \\ &= \frac{1}{\pi} \left[ \frac{|y-a|}{(y-a)^2 + (x-z)^2} \right] dz\end{aligned}$$

3. First observe,

$$u(x, a) = \frac{1}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) e^{-|a-a||\omega|} e^{i\omega x} d\omega = \frac{1}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) e^{i\omega x} d\omega = \phi(x)$$

Define,

$$c = \begin{cases} 1 & y \geq a \\ -1 & y < a \end{cases}$$

Now observe,

$$\partial_x^2 u(x, y) = \frac{1}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) e^{-c(y-a)|\omega|} \partial_x^2 e^{i\omega x} d\omega = \frac{(i^2 \omega^2)}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) e^{-c(y-a)|\omega|} e^{i\omega x} d\omega$$

Then,

$$\partial_y^2 u(x, y) = \frac{1}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) \partial_y^2 e^{-c(y-a)|\omega|} e^{i\omega x} d\omega = \frac{c^2 \omega^2}{2\pi} \int_{\mathbb{R}} \hat{\phi}(\omega) e^{-c(y-a)|\omega|} e^{i\omega x} d\omega$$

Thus, since  $i^2 = -1$  and  $c^2 = 1$ ,

$$(\partial_x^2 + \partial_y^2)u(x, y) = 0$$

Note there is probably some issue with the partial derivative with respect to  $y$  at  $y = a$ , since  $|y - a|$  is not differentiable at this point.

Therefore  $u(x, y) = \mathbb{E}[\phi(X_\tau) | X_t = x, Y_t = y]$  satisfies the PDE from 1.



**Exercise 10.1**

Let  $P = (P_t)_{t \geq 0}$  be a Poisson process with intensity  $\lambda$ .

- (a) What is the Lévy Measure  $\nu$  of  $P$ .
- (b) Let  $dX_t = dP_t$ . Define  $u(x, t) := \mathbb{E}[\varphi(X_T) | X_t = x]$ . Find  $u(t, x)$  and verify it solves the Kolmogorov Backward equation.

**Solution**

- (a) We have,

$$\nu(U) = \mathbb{E}[N(1, U)] = \mathbb{E}\left[\sum_{0 \leq s \leq 1} \mathbb{1}_{\Delta P_s \in U}\right] = \mathbb{E}\left[\sum_{i=1}^{P_1} \mathbb{1}_{1 \in U}\right] = \mathbb{E}[P_1] \mathbb{1}_{1 \in U} = \lambda \mathbb{1}_{1 \in U}$$

- (b) Integrating  $dX_t = dP_t$  from 0 to  $t$  gives,  $X_t - X_0 = P_t - P_0$ . Since  $P_0 = 0$  we have,

$$X_t = X_0 + P_t$$

First observe,

$$\mathbb{P}(X_T = k | X_t = x) = \mathbb{P}(X_0 + P_T = k | X_0 + P_t = x) = \mathbb{P}(P_T = k - X_0 | P_t = x - X_0)$$

Since  $P$  has independent increments, and since  $P$  is Markov,

$$\mathbb{P}(P_T = k - X_0 | P_t = x - X_0) = \mathbb{P}(P_{T-t} = k - x) = \frac{(\lambda(T-t))^{k-x}}{(k-x)!} e^{-\lambda(T-t)}$$

Thus,

$$u(t, x) = \mathbb{E}[\varphi(X_T) | X_t = x] = \sum_{k=x}^{\infty} \varphi(k) \mathbb{P}(X_T = k | X_t = x) = \sum_{k=x}^{\infty} \varphi(k) \frac{(\lambda(T-t))^{k-x}}{(k-x)!} e^{-\lambda(T-t)}$$

Reindexing with  $n = k - x$ ,

$$u(t, x) = e^{-\lambda(T-t)} \sum_{k=x}^{\infty} \varphi(k) \frac{(\lambda(T-t))^{k-x}}{(k-x)!} = e^{-\lambda(T-t)} \sum_{n=0}^{\infty} \varphi(n+x) \frac{(\lambda(T-t))^n}{n!}$$

We now compute the generator  $\mathcal{A}(t)$  for  $P$ . By definition,

$$\mathcal{A}(t)\varphi(x) = \lim_{s \rightarrow t^+} \frac{1}{s-t} [\mathcal{P}(t, s)\varphi(x) - \varphi(x)] = \lim_{s \rightarrow t^+} \frac{1}{s-t} [\mathbb{E}[\varphi(X_s)|X_t = x] - \varphi(x)]$$

In a small interval  $dt$  the probability  $X_{t+dt} = X_t + 1$  is  $\lambda dt$  and probability  $X_{t+dt} = X_t$  is  $(1 - \lambda)dt$ . Therefore,

$$\mathcal{A}(t)\varphi(x) = \frac{1}{dt} [\varphi(x+1)\lambda + \varphi(x)(1 - \lambda) - \varphi(x)] = \lambda(\varphi(x+1) - \varphi(x))$$

Since the  $t$ -derivative of the  $n = 0$  term is zero,

$$\begin{aligned} \sum_{n=0}^{\infty} \varphi(n+x) \partial_t \left[ \frac{(\lambda(T-t))^n}{n!} \right] &= \sum_{n=1}^{\infty} \varphi(n+x) \partial_t \left[ \frac{(\lambda(T-t))^n}{n!} \right] \\ &= \sum_{n=1}^{\infty} \varphi(n+x) (n) (-\lambda) \frac{(\lambda(T-t))^{n-1}}{n!} \\ &= -\lambda \sum_{n=1}^{\infty} \varphi(n+x) \frac{(\lambda(T-t))^{n-1}}{(n-1)!} \end{aligned}$$

Observe, by the chain rule and assuming we can bring a derivative through a sum,

$$\begin{aligned} \partial_t u(t, x) &= [\partial_t e^{-\lambda(T-t)}] \sum_{n=0}^{\infty} \varphi(n+x) \frac{(\lambda(T-t))^n}{n!} + e^{-\lambda(T-t)} \sum_{n=0}^{\infty} \varphi(n+x) \partial_t \left[ \frac{(\lambda(T-t))^n}{n!} \right] \\ &= \lambda e^{-\lambda(T-t)} \sum_{n=0}^{\infty} \varphi(n+x) \frac{(\lambda(T-t))^n}{n!} - \lambda e^{-\lambda(T-t)} \sum_{n=1}^{\infty} \varphi(n+x) \frac{(\lambda(T-t))^{n-1}}{(n-1)!} \\ &= \lambda e^{-\lambda(T-t)} \sum_{n=0}^{\infty} \varphi(n+x) \frac{(\lambda(T-t))^n}{n!} - \lambda e^{-\lambda(T-t)} \sum_{n=m}^{\infty} \varphi(m+1+x) \frac{(\lambda(T-t))^m}{m!} \\ &= \lambda(u(t, x) - u(t, x+1)) \end{aligned}$$

Therefore the KBE is satisfied as

$$[\partial_t + \mathcal{A}]u(t, x) = \lambda(u(t, x) - u(t, x+1)) - \lambda(u(t, x+1) - u(t, x)) = 0, \quad u(T, x) = \varphi(x)$$

**Exercise 10.2****Solution**

**Exercise 10.3**

Let  $X = (X_t)_{t \geq 0}$  be a process defined by,

$$\begin{aligned} dX_t &= \mu_t X_t dt + \sigma_t X_t dW_t + \int_{\mathbb{R}} (e^{\gamma_t(z)} - 1) X_{t-} \tilde{N}(dt, dz) \\ dY_t &= b_t Y_t dt + a_t Y_t dW_t + \int_{\mathbb{R}} (e^{g_t(z)} - 1) Y_{t-} \tilde{N}(dt, dz) \end{aligned}$$

where  $W$  is a one-dimensional Brownian motion,  $\tilde{N}$  is a one-dimensional compensated Poisson random measure on  $\mathbb{R}$ , and  $\mu, b, \sigma, a, \gamma, g$  are  $\mathbb{F}$ -adapted stochastic processes.

- (a) Define  $Z_t := X_t/Y_t$ . Compute the differential  $dZ_t$ . Your answer should not involve  $X_t$  or  $Y_t$ .
- (b) Find  $\mu_t$  so that  $Z$  is a martingale.

**Solution**

- (a) Define  $f(x, y) = x/y$ . Then  $Z_t = f(X_t, Y_t)$ .

We have,

$$[(e^{\gamma_t(z)} - 1)X_t; (e^{g_t(z)} - 1)Y_t] \cdot \nabla f(X_{t-}, Y_{t-}) = (e^{\gamma_t(z)} - 1)X_{t-} f_x(X_{t-}, Y_{t-}) + (e^{g_t(z)} - 1)Y_{t-} f_y(X_{t-}, Y_{t-})$$

We use Itô's formula to compute,

$$\begin{aligned} dZ_t = df(X_t, Y_t) &= \left( \mu_t X_t f_x + b_t Y_t f_y + \frac{1}{2} ((\sigma_t X_t)^2 f_{xx} + 2(\sigma_t X_t)(a_t Y_t) f_{xy} + (a_t Y_t)^2 f_{yy}) \right) dt \\ &\quad + (\sigma_t X_t f_x + a_t Y_t f_y) dW_t \\ &\quad + \int_{\mathbb{R}} (f(X_{t-} + (e^{\gamma_t(z)} - 1)X_{t-}, Y_{t-} + (e^{g_t(z)} - 1)Y_{t-}) - f(X_{t-}, Y_{t-})) \tilde{N}(dt, dz) \\ &\quad + \int_{\mathbb{R}} \left( f(X_{t-} + (e^{\gamma_t(z)} - 1)X_{t-}, Y_{t-} + (e^{g_t(z)} - 1)Y_{t-}) - f(X_{t-}, Y_{t-}) \right. \\ &\quad \left. - (e^{\gamma_t(z)} - 1)X_{t-} f_x(X_{t-}, Y_{t-}) - (e^{g_t(z)} - 1)Y_{t-} f_y(X_{t-}, Y_{t-}) \right) \nu(dz) dt \end{aligned}$$

Now, using  $f_x = 1/y$ ,  $f_y = -x/y^2$ ,  $f_{xy} = -1/y^2$ ,  $f_{xx} = 0$ ,  $f_{yy} = 2x/y^3$  we have,

$$\mu_t X_t f_x + b_t Y_t f_y = \mu_t X_t \left( \frac{1}{Y_t} \right) + b_t Y_t \left( \frac{-X_t}{Y_t^2} \right) = \mu_t Z_t - b_t Z_t$$

$$(\sigma_t X_t)^2 f_{xx} + 2(\sigma_t X_t)(a_t Y_t) f_{xy} + (a_t Y_t)^2 f_{yy} = 2(\sigma_t X_t)(a_t Y_t) \left( \frac{-1}{Y_t^2} \right) + a_t^2 Y_t^2 \left( \frac{2X_t}{Y_t^3} \right) = -2\sigma_t a_t Z_t + 2$$

$$\sigma_t X_t f_x + a_t Y_t f_y = \sigma_t X_t \left( \frac{1}{Y_t} \right) + a_t Y_t \left( \frac{-X_t}{Y_t^2} \right) = \sigma_t Z_t - a_t Z_t$$

$$f(X_{t-} + (e^{\gamma_t(z)} - 1)X_{t-}, Y_{t-} + (e^{g_t(z)} - 1)Y_{t-}) - f(X_{t-}, Y_{t-}) = \frac{e^{\gamma_t(z)}}{e^{g_t(z)}} Z_{t-} - Z_{t-}$$

$$\begin{aligned} & (e^{\gamma_t(z)} - 1)X_{t-} f_x(X_{t-}, Y_{t-}) + (e^{g_t(z)} - 1)Y_{t-} f_y(X_{t-}, Y_{t-}) \\ &= (e^{\gamma_t(z)} - 1)X_{t-} \left( \frac{1}{Y_{t-}} \right) + (e^{g_t(z)} - 1)Y_{t-} \left( \frac{-X_{t-}}{Y_{t-}^2} \right) \\ &= (e^{\gamma_t(z)} - 1)Z_{t-} - (e^{g_t(z)} - 1)Z_{t-} \end{aligned}$$

Inserting these evaluated expressions into the original expression for  $dZ_t$  gives,

$$\begin{aligned} dZ_t &= (\mu_t - b_t - \sigma_t a_t + a_t^2) Z_t dt + (\sigma_t - a_t) Z_t dW_t \\ &\quad + \int_{\mathbb{R}} \left( \frac{e^{\gamma_t(z)}}{e^{g_t(z)}} - 1 \right) Z_{t-} \tilde{N}(dt, dz) \\ &\quad + \int_{\mathbb{R}} \left( \frac{e^{\gamma_t(z)}}{e^{g_t(z)}} - e^{\gamma_t(z)} + e^{g_t(z)} - 1 \right) Z_{t-} \nu(dz) dt \end{aligned}$$

(b) We need the  $dt$  term to be zero. Therefore pick,

$$\mu_t = b_t + \sigma_t a_t - a_t^2 - \int_{\mathbb{R}} \left( \frac{e^{\gamma_t(z)}}{e^{g_t(z)}} - e^{\gamma_t(z)} + e^{g_t(z)} - 1 \right) \nu(dz) dt$$

**Exercise 10.4**

Let  $\eta = (\eta_t)_{t \geq 0}$  be a one-dimensional Lévy Process and define  $X = (X_t)_{t \geq 0}$  by

$$dX_t = \kappa(\theta - X_t)dt + d\eta_t$$

- (a) Find  $X_t$  explicitly as a function of  $\eta$ .
- (b) Assume  $\eta_t = \sigma W_t + \int_{\mathbb{R}} z \tilde{N}(t, dz)$ . Compute  $m(t) := \mathbb{E}X_t$  and  $c(t, s) := \mathbb{E}(X_t - m(t))(X_s - m(s))$ .

**Solution**

- (a) Let  $Y_t = X_t - \theta$  and  $Z_t = e^{\kappa t} Y_t = f(t, Y_t)$ , where  $f(t, y) = e^{\kappa t} y$ .

Then,

$$dY_t = dX_t = -\kappa Y_t dt + d\eta_t$$

Recall the product rule (which applies to Lévy Itô processes),

$$d(U_t V_t) = U_{t-} dV_t + V_{t-} dU_t + d[U, V]_t$$

Therefore,

$$dZ_t = d(e^{\kappa t} Y_t) = e^{\kappa t-} dY_t + Y_{t-} de^{\kappa t} + d[e^{\kappa t}, Y]_t$$

Using our heuristics we have  $d(e^{\kappa t})dY_t = 0$ . Therefore, since  $t^-$  and  $t$  can be “treated the same” on  $dt$  terms which are continuous,

$$dZ_t = e^{\kappa t-} dY_t + \kappa e^{\kappa t} Y_{t-} = e^{\kappa t-} d\eta_t$$

Integrating we have,

$$Z_t = Z_0 + \int_0^t e^{\kappa s} d\eta_s$$

Therefore, since  $Y_t = e^{-\kappa t} Z_t$ ,  $Z_0 = Y_0$  so,

$$Y_t = e^{-\kappa t} \left( Y_0 + \int_0^t e^{\kappa s} d\eta_s \right)$$

Finally, since  $X_t = \theta + Y_t$ ,  $Y_0 = X_0 - \theta$  so,

$$X_t = \theta + e^{-\kappa t} \left( X_0 - \theta + \int_0^t e^{\kappa s} d\eta_s \right) = \theta + e^{-\kappa t} (X_0 - \theta) + \int_0^t e^{\kappa(s-t)} d\eta_s$$

(b) We have,

$$d\eta_t = \sigma dW_t + \int_{\mathbb{R}} z \tilde{N}(dt, dz)$$

Observe, that since integrals with respect to  $dW_t$  and  $\int_{\mathbb{R}} \tilde{N}(dt, dz)$  are martingales so,

$$\mathbb{E} \left[ \int_0^t e^{\kappa(s-t)} d\eta_s \right] = \mathbb{E} \left[ \int_0^t e^{\kappa(s-t)} \sigma dW_t + \int_0^t e^{\kappa(s-t)} \int_{\mathbb{R}} z \tilde{N}(dt, dz) \right] = 0$$

Therefore,

$$m(t) = \mathbb{E} [X_t] = \mathbb{E} \left[ \theta + e^{-\kappa t} (X_0 - \theta) + \int_0^t e^{\kappa(s-t)} d\eta_s \right] = \theta + e^{-\kappa t} (X_0 - \theta)$$

Clearly,

$$X_t - m(t) = \int_0^t e^{\kappa(u-t)} d\eta_u$$

Without loss of generality assume  $t \geq s$ . Then, using the independent increments property to write the expectation of a product as the product of expectations,

$$\begin{aligned} \mathbb{E} [(X_t - m(t)) (X_s - m(s))] &= \mathbb{E} \left[ \left( \int_0^t e^{\kappa(u-t)} d\eta_u \right) \left( \int_0^s e^{\kappa(v-s)} d\eta_v \right) \right] \\ &= \mathbb{E} \left[ \left( \int_0^s e^{\kappa(u-t)} d\eta_u + \int_s^t e^{\kappa(u-t)} d\eta_u \right) \left( \int_0^s e^{\kappa(v-s)} d\eta_v \right) \right] \\ &= \mathbb{E} \left[ e^{-\kappa(t+s)} \left( \int_0^s e^{\kappa u} d\eta_u \right)^2 + e^{-\kappa(t+s)} \left( \int_s^t e^{\kappa u} d\eta_u \right) \left( \int_0^s e^{\kappa v} d\eta_v \right) \right] \\ &= e^{-\kappa(t+s)} \mathbb{E} \left[ \left( \int_0^s e^{\kappa u} d\eta_u \right)^2 \right] + e^{-\kappa(t+s)} \mathbb{E} \left[ \int_s^t e^{\kappa u} d\eta_u \right] \mathbb{E} \left[ \int_0^s e^{\kappa v} d\eta_v \right] \end{aligned}$$

We now note that, Lévy processes without a  $dt$  term are martingales so that,

$$\mathbb{E} \left[ \int_0^s e^{\kappa u} d\eta_u \right] = \mathbb{E} \left[ \int_0^s e^{\kappa u} \left( \sigma dW_u + \int_{\mathbb{R}} z \tilde{N}(du, dz) \right) \right] = 0$$

Define,

$$Z_s = \int_0^s e^{\kappa u} d\eta_u$$

Then,

$$dZ_s = e^{\kappa s} d\eta_s = \sigma e^{\kappa s} dW_s + \int_{\mathbb{R}} e^{\kappa s} z \tilde{N}(ds, dz)$$

Using Itô's isometry we have,

$$\mathbb{E} \left[ \left( \int_0^s e^{\kappa u} d\eta_u \right)^2 \right] = \mathbb{E} \left[ \int_0^s \left( \sigma^2 e^{2\kappa u} + \int_{\mathbb{R}} e^{2\kappa u} z^2 \nu(dz) \right) du \right] = \mathbb{E} \left[ \left( \sigma^2 + \int_{\mathbb{R}} z^2 \nu(dz) \right) \frac{e^{2\kappa s} - 1}{2\kappa} \right]$$

Therefore,

$$c(t, s) = e^{-\kappa(t+s)} \frac{e^{2\kappa s} - 1}{2\kappa} \left( \sigma^2 + \int_{\mathbb{R}} z^2 \nu(dz) \right) = \frac{e^{\kappa(s-t)} - e^{-\kappa(t+s)}}{2\kappa} \left( \sigma^2 + \int_{\mathbb{R}} z^2 \nu(dz) \right)$$

We can remove our assumption that  $t \geq s$  and write,

$$c(t, s) = \frac{e^{-\kappa|t-s|} - e^{-\kappa(t+s)}}{2\kappa} \left( \sigma^2 + \int_{\mathbb{R}} z^2 \nu(dz) \right)$$



**Exercise 10.5**

Let  $X$  be the following one-dimensional jump-diffusion

$$dX_t = \mu(t, X_t)dt + \sigma(t, X_t)dW_t + \int_{\mathbb{R}} \gamma(t, X_{t-}, z)\tilde{N}(t, dz),$$

where  $W$  is a one-dimensional Brownian motion and  $\tilde{N}$  is a one-dimensional compensated Poisson random measure on  $\mathbb{R}$ . Derive using the Lévy-Itô formula the infinitesimal generator  $\mathcal{A}(t)$  of the  $X$  process,

$$\mathcal{A}(t)\varphi(x) := \lim_{s \rightarrow t^+} \frac{\mathbb{E}[\varphi(X_s)|X_t = x] - \varphi(x)}{s - t}$$

**Solution**

Since  $\mathbb{E}[\varphi(X_t)|X_t = x] = \varphi(x)$ ,

$$\mathbb{E}[\varphi(X_s)|X_t = x] - \varphi(x) = \mathbb{E}\left[\varphi(X_t) + \int_t^s d\varphi(X_u)\right] - \varphi(x) = \mathbb{E}\left[\int_t^s d\varphi(X_u)\right]$$

From the Lévy-Itô formula we have,

$$\begin{aligned} d\varphi(X_u) &= \left(\mu(u, X_u)\varphi'(X_u) + \frac{1}{2}\sigma(u, X_u)^2\varphi''(X_u)\right)du + \sigma(u, X_u)\varphi'(X_u)dW_u \\ &\quad + \int_{\mathbb{R}} \left(\varphi(X_{u-} + \gamma(u, X_{u-}, z)) - \varphi(X_{u-})\right)\tilde{N}(du, dz) \\ &\quad + \int_{\mathbb{R}} \left(\varphi(X_{u-} + \gamma(u, X_{u-}, z)) - \varphi(X_{u-}) - \gamma(u, X_{u-}, z)\varphi'(X_{u-})\right)\nu(dz)du \end{aligned}$$

We note that as integrals with respect to  $W$  and  $\tilde{N}$  are martingales that,

$$\begin{aligned} \mathbb{E}\left[\int_t^s d\varphi(X_u)\right] &= \mathbb{E}\left[\int_t^s \left(\mu(u, X_u)\varphi'(X_u) + \frac{1}{2}\sigma(u, X_u)^2\varphi''(X_u)du\right.\right. \\ &\quad \left.\left.+ \int_{\mathbb{R}} \left(\varphi(X_{u-} + \gamma(u, X_{u-}, z)) - \varphi(X_{u-}) - \gamma(u, X_{u-}, z)\varphi'(X_{u-})\right)\nu(dz)\right)du\right] \end{aligned}$$

Thus, taking the limit as  $s \rightarrow t^+$ ,

$$\mathcal{A}(t)\varphi(x) = \left(\mu(t, X_t)\partial_x + \frac{1}{2}\sigma(t, X_t)\partial_x^2 + \int_{\mathbb{R}} \nu(dz) (\theta_{\gamma(t, X_t, z)} - 1 - \gamma(t, X_t, z)\partial_x)\right)\varphi(x)$$