

# EECS126 Course Notes [Spring 2021]

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## 1 Note

These course notes are my notes from EECS 126 : Probability and Random Processes. The course is [linked here](#). These course notes are in progress.

## 2 Probability Basics

For this section, since this is mostly review, I will brush over most topics and state them without proof.

### 2.1 Probability Fundamentals

**Definition 2.1** (Probability Space). A probability space is a triple  $(\Omega, \mathcal{F}, P)$  where  $\Omega$  is the sample space,  $\mathcal{F}$  is the family of subsets of  $\Omega$ , and  $P$  is the probability measure.

Technical Assumption:  $\mathcal{F}$  is a  $\sigma$ -algebra containing  $\Omega$  itself, meaning that the countable complements/unions/intersections of events are events.

**Definition 2.2** (Kolmogorov Axioms). Probability measures must obey the Kolmogorov Axioms:

- $P(A) \geq 0 \quad \forall A \in \mathcal{F}$
- $P(\Omega) = 1$
- If  $A_1, A_2, \dots \in \mathcal{F}$  and  $A_i \cap A_j = \emptyset \quad \forall i \neq j$ , then  $P(\cup_{i \geq 1} A_i) = \sum_{i \geq 1} P(A_i)$

**Theorem 1** (Law of Total Probability). If  $A_i$  are disjoint and  $\cup_{i \geq 1} A_i = \Omega$ , then  $P(B) = \sum_{i \geq 1} P(A_i \cap B)$ .

**Definition 2.3** (Conditional Probability). If  $B$  is an event with  $P(B) > 0$ , then conditional probability of  $A$  given  $B$  is  $P(A|B) := \frac{P(A \cap B)}{P(B)}$ .

**Theorem 2** (Bayes Rule). If events  $A$  and  $B$  have positive probability, then  $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$ .

**Definition 2.4** (Independence). Events  $A, B$  are independent if  $P(A \cap B) = P(A)P(B)$ .

**Definition 2.5** (Conditional Independence). If events  $A, B, C$  with  $P(C) > 0$  satisfy  $P(A \cap B|C) = P(A|C)P(B|C)$ .

### 2.2 Random Variable

**Definition 2.6.** A random variable is a function  $X : \Omega \rightarrow \mathbb{R}$  with the property  $\{\omega \in \Omega : X(\omega) \leq \alpha\} \in \mathcal{F} \quad \forall \alpha \in \mathbb{R}$ .

This means that  $P(X \leq \alpha) := P(\{\omega \in \Omega : X(\omega) \leq \alpha\})$ . Technical definition of r.v. implies that

- If  $X, Y$  are r.v.s, then so is  $X + Y, XY, X^p$  where  $p \in \mathbb{R}$
- If  $X_1, X_2, \dots$  are r.v.s, then so is  $\lim_{n \rightarrow \infty} X_n$

**Definition 2.7** (Discrete Random Variables). A discrete r.v. is a r.v. that takes countably many values.

**Definition 2.8** (Continuous Random Variables). A continuous r.v. is a r.v. defined via its density  $f_X : \mathbb{R} \rightarrow [0, \infty)$ . So  $Pr\{X \in B\} = \int_B f_X(x)dx$  where  $f_X \geq 0$  and  $\int_{\mathbb{R}} f_X(x)dx = 1$ .

## 2.3 Expectation

**Definition 2.9** (Expectation). For a discrete r.v.  $X$ , its expectation is  $\mathbb{E}[X] = \sum_{x \in X} xp_x(x)$  provided that the series exists. For a continuous r.v., its expectation is  $\mathbb{E}[X] = \int_{\mathbb{R}} xf_X(x)dx$ . More generally,  $\mathbb{E}[g(X_1, \dots, X_n)] = \int \dots \int_{\mathbb{R}^n} g(x_1, \dots, x_n)f_{X_1, \dots, X_n}(x_1, \dots, x_n)dx_1 \dots dx_n$

**Theorem 3** (Law of the Unconscious Statistician). If  $Y = g(X)$  and  $g : X \rightarrow \mathbb{R}$ , then  $Y$  is a r.v. and  $\mathbb{E}[Y] = \sum_{x \in X} g(x)p_X(x)$ .

**Theorem 4** (Linearity of Expectation).  $\mathbb{E}[aX + bY] = a\mathbb{E}[X] + b\mathbb{E}[Y]$  where  $a, b \in \mathbb{R}$ .

**Theorem 5** (Product of Expectation of Independent R.V.s). If  $X, Y$  are independent random variables,  $\mathbb{E}[XY] = \mathbb{E}[X]\mathbb{E}[Y]$

**Theorem 6** (Tail Sum Formula for Expectation). For a discrete r.v.,  $\mathbb{E}[X] = \sum_{k=1}^{\infty} Pr\{X \geq k\}$

## 2.4 Variance, Covariance, and Correlation

**Definition 2.10** (Variance).  $Var(X) := \mathbb{E}[(X - \mathbb{E}[X])^2] = \mathbb{E}[X^2] - (\mathbb{E}[X])^2$

**Theorem 7** (Sum of Variances of Independent R.V.s). If  $X, Y$  are independent, then  $Var(X + Y) = Var(X) + Var(Y)$ .

**Definition 2.11** (Covariance).  $Cov(X, Y) = \mathbb{E}[(X - \mathbb{E}[X])(Y - \mathbb{E}[Y])]$

$X, Y$  independent  $\implies Cov(X, Y) = 0 \iff X, Y$  are uncorrected

**Definition 2.12** (Correlation Coefficient).  $\rho(X, Y) := \frac{Cov(X, Y)}{\sigma_X \sigma_Y}$

Note that  $|\rho(X, Y)| \leq 1$ .

## 2.5 Multiple Random Variables

**Definition 2.13** (Conditional Expectation). If  $X$  is a discrete r.v.,  $\mathbb{E}[X|Y = y] := \sum_{x \in X} xp_{X|Y}(x|y)$ . If  $Y$  is a continuous r.v.,  $\mathbb{E}[X|Y = y] := \int xf_{X|Y}(x|y)dx$ .

**Theorem 8** (Tower Property).  $\mathbb{E}[f(Y)X] = \mathbb{E}[f(Y)\mathbb{E}[X|Y]]$

If  $f(Y) = 1$ , then  $\mathbb{E}[\mathbb{E}[X|Y]] = \mathbb{E}[X]$ .

**Definition 2.14** (Conditional Variance).  $\text{Var}(X|Y = y) = \mathbb{E}[(X - \mathbb{E}[X|Y = y])^2|Y = y] = \mathbb{E}[X^2|Y = y] - (\mathbb{E}[X|Y = y])^2$

**Definition 2.15** (Minimum Mean Square Error (MMSE)).  $\mathbb{E}[\text{Var}(X|Y)] = \mathbb{E}[(X - \mathbb{E}(X|Y))^2]$

**Theorem 9** (Law of Total Variance).  $\text{Var}(X) = \mathbb{E}[\text{Var}(X|Y)] + \text{Var}(\mathbb{E}[X|Y])$

## 2.6 Notes on Distributions

### 2.6.1 Exponential

$\text{Exp}(\lambda)$  is the unique continuous r.v. with the memoryless property:  $P(X > t + s | X > s) = P(X > t) \quad \forall s, t \geq 0$ . Also note that if  $X_i$  are independent exponentials with parameter  $\lambda_i$ , then  $P(X_i = \min_{1 \leq k \leq n} X_k) = \frac{\lambda_i}{\sum_{j=1}^n \lambda_j}$  because  $\min_{1 \leq k \leq n} X_k \sim \text{Exp}(\sum_{j=1}^n \lambda_j)$ .

## 2.7 Order Statistics

Let  $X_1, \dots, X_n$  be IID and sort them so that  $X^{(1)} \leq \dots \leq X^{(n)}$ . Then

$$f_{X^{(i)}}(y) = n \binom{n-1}{i-1} F_X(y)^{i-1} (1 - F_X(y))^{n-i} f_X(y)$$

## 2.8 Moment Generating Function

A moment generating function (MGF) encodes moments of a distribution into coefficients of some power series.

$$M_X(t) := \mathbb{E}[e^{tX}] = \mathbb{E}\left[\sum_{n \geq 0} \frac{(tX)^n}{n!}\right] = \sum_{n \geq 0} \frac{t^n}{n!} \mathbb{E}[X^n] \quad t \in \mathbb{R}$$

In fact, if an MGF exists, it uniquely determines the distribution of  $X$ . To recover the  $n$ th moment we simply do

$$\frac{d^n}{dt^n} M_X(t)|_{t=0} = \mathbb{E}[X^n]$$

## 2.9 Concentration Inequalities

**Theorem 10** (Markov Inequality). *If  $X$  is non-negative r.v.,  $P(X \geq t) \leq \frac{\mathbb{E}[X]}{t} \quad t > 0$*

**Theorem 11** (Chebyshev's Inequality).  $P(|X - \mathbb{E}[X]| \geq t) \leq \frac{\text{Var}(X)}{t^2}$

**Theorem 12** (Chernoff Bound).  $P(X \geq a) \leq \frac{\mathbb{E}[e^{tX}]}{e^{ta}} = e^{-ta} M_X(t) \quad t > 0$

## 2.10 Convergence of Random Variables

**Definition 2.16.** Three modes of convergence:

- Almost Sure Convergence:  $X_n \rightarrow X$  a.s. if  $P(\lim_{n \rightarrow \infty} X_n = X) = 1$
- Convergence in Probability:  $X_n \rightarrow X$  i.p if  $\lim_{n \rightarrow \infty} P(|X_n - X| > \epsilon) = 0$  for  $\epsilon > 0$
- Convergence in Distribution:  $X_n \rightarrow X$  i.d. if  $\lim_{n \rightarrow \infty} F_{X_n}(x) = F_X(x)$  for all continuity points  $x$  of  $F_X$

Note that  $a.s. \implies i.p \implies i.d.$

**Theorem 13** (Weak Law of Large Numbers (WLLN)).  $\frac{1}{N} \sum_{i=1}^N X_i \rightarrow \mathbb{E}[X]$  in probability if  $X_i$  are IID and  $\mathbb{E}[|X|] < \infty$ .

**Theorem 14** (Strong Law of Large Numbers (SLLN)).  $\frac{1}{N} \sum_{i=1}^N X_i \rightarrow \mathbb{E}[X]$  almost surely if  $X_i$  are IID and  $\mathbb{E}[|X|] < \infty$ .

**Theorem 15** (Central Limit Theorem (CLT)). Let  $X_i$  be IID and  $\text{Var}(X) = \sigma^2 < \infty$  and  $\mathbb{E}[X] = \mu$ . We define  $S_n = \frac{\sum_{i=1}^n (X_i - \mu)}{\sqrt{n}\sigma}$ . Then  $S_n \rightarrow \mathcal{N}(0, 1)$  i.d.

Problem Solving Strategies: For i.p. convergence, try Chebyshev.



### 3 Information Theory

#### 3.1 Definitions

**Definition 3.1** (Entropy).  $\mathcal{H}(X) := \sum_x p_X(x) \log \frac{1}{p_X(x)} = \mathbb{E}[\log \frac{1}{p_X(X)}]$

**Definition 3.2** (Conditional Entropy). The conditional entropy is the average amount of uncertainty remaining in random variable  $X$  after observing  $Y$ .

$$\begin{aligned} H(X|Y) &= \sum_{y \in \mathcal{Y}} p_Y(y) H(X|Y=y) \\ &= \sum_{y \in \mathcal{Y}} p_Y(y) \sum_{x \in \mathcal{X}} p_{X|Y}(x|y) \log_2 \frac{1}{p_{X|Y}(x|y)} \\ &= - \sum_{y \in \mathcal{Y}, x \in \mathcal{X}} p_{X,Y}(x,y) \log_2 \frac{p_{X,Y}(x,y)}{p_Y(y)} \end{aligned}$$

**Definition 3.3** (Mutual Information). The mutual information is the amount of information about  $X$  gained by observing  $Y$ .

$$\begin{aligned} I(X; Y) &:= \sum p_{XY}(x,y) \log \frac{p_{XY}(x,y)}{p_X(x)p_Y(y)} \\ &= H(X) - H(X|Y) \end{aligned}$$

**Theorem 16.**  $H(X, Y) = H(Y) + H(X|Y) = H(X) + H(Y|X)$

**Theorem 17.**  $I(X; Y) = H(X) + H(Y) - H(X, Y) = I(Y; X)$

**Theorem 18.**  $H(X|Y) \leq H(X)$

**Theorem 19.** If  $X_1$  and  $X_2$  are independent r.v.,  $H(X_1 + X_2) \geq H(X_1)$

#### 3.2 Asymptotic Equipartition Theorem (AEP)

**Theorem 20** (AEP). If  $(X_i)_{i \geq 1} \stackrel{IID}{\sim} p_X$ , then  $-\frac{1}{n} \log p(X_1, \dots, X_n) \rightarrow \mathcal{H}(X)$  i.p.

*Proof.* By WLLN,  $-\frac{1}{n} \log p(X_1, \dots, X_n) = \frac{1}{n} \sum_{i=1}^n \log \frac{1}{p_X(X_i)} \rightarrow \mathbb{E}[\log \frac{1}{p_X(X)}] = \mathcal{H}(X)$  i.p.  $\square$

In other words, with overwhelming probability, we see that  $p(X_1, \dots, X_n) \approx 2^{-nH(X)}$ .

**Definition 3.4** (Typical Set). Fix  $\epsilon > 0$  and for each  $n \geq 1$  define the typical set:

$$A_\epsilon^{(n)} = \{(X_1, \dots, X_n) : p(X_1, \dots, X_n) \geq 2^{-n(H(X)+\epsilon)}\}$$

- $P((X_1, \dots, X_n) \in A_\epsilon^{(n)}) \rightarrow 1$  as  $n \rightarrow \infty$  by AEP

- $|A_\epsilon^{(n)}| \leq 2^{n(H(X)+\epsilon)}$  because

$$1 \geq \sum_{(X_1, \dots, X_n) \in A_\epsilon^{(n)}} p(X_1, \dots, X_n) \geq \sum_{(X_1, \dots, X_n) \in A_\epsilon^{(n)}} 2^{-n(H(X)+\epsilon)} = |A_\epsilon^{(n)}| 2^{-n(H(X)+\epsilon)}$$

### 3.3 Source Coding Theorem

**Theorem 21** (Source Coding Theorem). *For any  $\epsilon > 0$ , IID discrete r.v.s  $X_i$  can be losslessly represented using  $\leq n(H(X) + \epsilon)$  bits (for all  $n$  sufficiently large). Conversely, any representation using  $< nH(X)$  bits is impossible without loss of information.*

*Proof.* We will prove the achievability part of the theorem. Our protocol for source coding will be:

- If I observe  $(X_1, \dots, X_n) \in A_{\epsilon/2}^{(n)}$ , I will describe it using  $\sim \log |A_{\epsilon/2}^{(n)}|$  bits  $\leq n(H(X) + \epsilon/2)$
- If I observe  $(X_1, \dots, X_n) \notin A_{\epsilon/2}^{(n)}$ , I just describe it brute force using  $n \log |X|$  bits.

Then

$$\begin{aligned} \mathbb{E}[\# \text{ bits}] &\leq n(H(X) + \frac{\epsilon}{2})P((X_1, \dots, X_n) \in A_{\epsilon/2}^{(n)}) + n \log |X| P((X_1, \dots, X_n) \notin A_{\epsilon/2}^{(n)}) \\ &\leq n(H(X) + \epsilon) \text{ for all } n \text{ sufficiently large} \end{aligned}$$

□

### 3.4 Information Transmission

Fix a rate  $R > 0$ , send message  $M \sim \text{Uniform}(1 \dots 2^{nR})$ . It takes  $nR$  bits to represent  $H(M) = nR$ . The message is encoded into  $X^n(M)$ , put through a noisy channel to become  $Y^n$ , and then decoded to become  $\hat{M}(Y^n)$ . The rate  $R = \frac{H(M)}{n}$  and the error probability  $P_e^{(n)} := P(\hat{M} \neq M)$ .

**Definition 3.5** (Capacity).  $C = \max_{p_X} I(X; Y) = \max$  mutual info between channel input and output over all input distributions

**Theorem 22** (Shannon's Channel Coding Theorem). *Fix channel  $p_{Y|X}$ ,  $\epsilon > 0$ , and  $R < C$ .*

- *For all  $n$  sufficiently large, there exists rate- $R$  communication scheme (encoder/decoder) that achieves  $P_e^{(n)} < \epsilon$*
- *If  $R > C$ , then  $P_e^{(n)} \rightarrow 1$  for any sequence of communication schemes.*

**Definition 3.6** (Binary Symmetric Channel (BSC)). In BSC( $p$ ), each input is flipped independently with probability  $p$ .  $C = 1 - H_2(p)$  where  $H_2(p) = p \log \frac{1}{p} + (1-p) \log \frac{1}{1-p}$ .

**Definition 3.7** (Binary Erasure Channel (BEC)). In BEC( $p$ ), each input is erased independently with probability  $p$ .  $C = 1 - p$ .

*Proof of Channel Coding Theorem for BEC(p).* Suppose we have  $n$  channel uses and knew which positions were erased and un-erased. There are then  $\leq n(1 - p + \epsilon)$  unerased positions with overwhelming probability for any  $\epsilon > 0$  and  $n$  sufficiently large. We can only reliably send  $\approx n(1 - p)$  bits so  $R \leq 1 - p$ . So we have proved that for  $R > C$ , this is not possible.

To prove that  $R < C$  allows reliable communication, we fix  $R < 1 - p - \epsilon$  and generate a random matrix  $C \in \mathbb{R}^{(n \times 2^{nR})}$  such that  $C_{ij} \stackrel{IID}{\sim} B(1/2)$ . Our protocol is to give  $C$  to both the encoder and decoder, send row  $M$  of  $C$ , and on receiving  $Y^n$  look for row in  $C$  that matches modulo erasures (error if  $\geq 2$  rows match what was received).

$$\begin{aligned}
\mathbb{E}_c[P_\epsilon^{(n)}] &= \sum_{E \subset [n]} \mathbb{E}[1\{\hat{M} \neq M\} | E] P(\text{bits erased} = E) \\
&\leq \sum_{E: |E| \leq n(p+\epsilon/2)} \mathbb{E}[1\{\hat{M} \neq M\} | E] P(E) + P\left(\frac{1}{n}|E| > p + \epsilon/2\right) \\
&\leq \sum_{E: |E| \leq n(p+\epsilon/2)} P(\cup_{m \geq 2}^{2^{nR}} \{C(1, [n] \setminus E) = C(m, [n] \setminus E)\} | E) P(E) \\
&\leq \sum_{E: |E| \leq n(p+\epsilon/2)} \sum_{m \geq 2}^{2^{nR}} \left(\frac{1}{2}\right)^{n-|E|} P(E) \\
&\leq \sum_{E: |E| \leq n(p+\epsilon/2)} 2^{-n\epsilon} P(E) \\
&\rightarrow 0 \text{ as } n \rightarrow \infty
\end{aligned}$$

So there must exist some sufficiently large  $n$  such that  $P_\epsilon^{(n)} < \epsilon$ . Note that in line 2, the right hand term goes to zero as  $n$  goes to infinity.  $\square$

## 4 Discrete Time Markov Chains (DTMCs)

### 4.1 Construction

**Definition 4.1** (Markov Chain).  $(X_n)_{n \geq 0}$  is a MC if each r.v.  $X_i$  is a discrete r.v. taking values in discrete set  $S$ , and for all  $n \geq 0$  and  $i, j \in S$

$$P(X_{n+1} = j | X_n = i, X_{n-1} = x_{n-1}, \dots, X_0 = x_0) = P(X_{n+1} | X_n = i)$$

For this course, we will be workly only with temporally homogeneous markov chains.

**Definition 4.2** (Temporally Homogeneous Markov Chains). For temporally homogeneous markov chains,  $P(X_{n+1} = j | X_n = i) = p_{ij}$ . In other words, transition probabilities don't depend on time.

**Theorem 23** (Chapman-Kolmogorov Equations). *n-step transition probabilities can be computed as  $P_{ij}^n = [P^n]_{ij}$ . Note that  $P(X_n = j | X_0 = i) := P_{ij}^n$ .*

### 4.2 Classification of States

If there is a path from  $i$  to  $j$ , then we say  $i \rightarrow j$ . If there is also path from  $j$  to  $i$ , then  $i$  and  $j$  communicate (i.e.  $i \leftrightarrow j$ ).  $\leftrightarrow$  is an equivalence relation on  $S$ . In other words, it partitions  $S$  into classes of communicating states.

**Definition 4.3** (Irreducible). A MC is irreducible if it has only one class.

Define  $T_i = \min\{n \geq 1 : X_n = i\}$  and  $\text{period}(i) := \text{GCD}\{n \geq 1 : P_{ii}^n > 0\}$ . So aperiodic means period is 1. Below are a list of class properties:

- Recurrent if process starting at start  $i$  revisits state  $i$  with probability one
- Transient if it is not recurrent
- Positive Recurrent if recurrent and  $\mathbb{E}[T_i | X_0 = i] < \infty$
- Null Recurrent if recurrent and  $\mathbb{E}[T_i | X_0 = i] = \infty$
- Periodicity (i.e. period is the same in same class)

### 4.3 Big Theorem

**Definition 4.4** (Stationary Distribution). A probability distribution  $\pi = (\pi_i)_{i \in S}$  is said to be a stationary distribution if  $\pi = \pi P$ . In other words,  $\pi_j = \sum_{i \in S} \pi_i p_{ij} \quad \forall j \in S$ .

**Theorem 24** (Big Theorem for Markov Chains). *Let  $(X_n)_{n \geq 0}$  be an irreducible MC. Exactly one of the following is true:*

1. *Either all states are transient, or all are null recurrent. In this case, no stationary distribution exists, and  $\lim_{n \rightarrow \infty} P_{ij}^n = 0$  for all  $i, j \in S$*

2. All states are positive recurrent. In this case, a stationary distribution  $\pi$  exists. It is unique and satisfies

$$\pi_j = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{k=1}^n P_{ij}^k = \frac{1}{\mathbb{E}[T_j | x_0 = j]}$$

Moreover, if the MC is aperiodic, then

$$\lim_{n \rightarrow \infty} P_{ij}^n = \pi_j \quad \forall i, j \in S$$

In fact, every finite-state MC is positive recurrent.

**Definition 4.5** (Reversible). An irreducible MC is reversible if there exists a probability vector  $\pi$  satisfying  $\pi_j P_{ji} = \pi_i P_{ij} \quad \forall i, j \in S$ . These are called the detailed balance equations.

If a MC is reversible, then  $\pi$  is a stationary distribution. (also unique by Big Theorem) Also note that MC trees satisfy DBE due to flow-in equals flow-out for any cut of MC. Therefore, examples like birth-death chains are reversible.

#### 4.4 First Step Equations (FSE)

Consider  $A \subset S$ , and define hitting time as  $T_A = \min\{n \geq 0 : X_n \in A\}$ . This is hard to do so we will instead try to compute  $t_i = \mathbb{E}[T_A | X_0 = i]$ . We can compute this by formulating first step equations:

- For  $i \notin A$ ,  $t_i = 1 + \sum_{j \in S} p_{ij} t_j$
- For  $i \in A$ ,  $t_i = 0$

## 5 Poisson Processes

### 5.1 Construction

A Poisson Process is an example of a counting process. A counting process  $(N_t)_{t \geq 0}$  is a non-decreasing continuous-time integer-valued random process, which has right continuous sample paths.

**Definition 5.1** (Poisson Process). A rate- $\lambda$  Poisson Process (i.e.  $PP(\lambda)$ ) is a counting process with i.i.d inter-arrival times  $S_i \stackrel{\text{iid}}{\sim} \text{Exp}(\lambda)$ . Equivalently, a counting process is  $PP(\lambda)$  iff  $N_0 = 0$ ,  $N_t - N_s \sim \text{Poisson}(\lambda(t-s))$  for  $0 \leq s \leq t$ , and  $(N_t)_{t \geq 0}$  has independent increments.

To elaborate on this, we will define  $T_i$  to be the arrival times, so  $T_i = \min\{t \geq 0 : N_t \geq i\}$ , which is the time of  $i$ th arrival. We also define the inter-arrival time,  $S_i = T_i - T_{i-1}$ , for  $i \geq 1$ .

**Theorem 25.** If  $(N_t)_{t \geq 0}$  is a  $PP(\lambda)$ , then for  $t \geq 0$ ,  $N_t \sim \text{Poisson}(\lambda t)$ . I.e.  $Pr\{N_t = n\} = \frac{e^{-\lambda t}(\lambda t)^n}{n!}$

*Proof.*

$$\begin{aligned}
 Pr\{N_t = n\} &= Pr\{T_n \leq t < T_{n+1}\} \\
 &= \mathbb{E}[\mathbb{1}_{\{T_n \leq t\}} \mathbb{1}_{\{t \leq T_{n+1}\}}] \\
 &= \int f_{T_n}(s) \mathbb{1}_{\{s \leq t\}} \mathbb{E}[\mathbb{1}_{\{t \leq s + S_{n+1}\}}] ds \\
 &= \int_0^t f_{T_n}(s) \mathbb{E}[\mathbb{1}_{\{t-s \leq S_{n+1}\}}] ds \\
 &= \int_0^t f_{T_n}(s) e^{-\lambda(t-s)} ds \\
 &= \int_0^t \frac{\lambda e^{-\lambda s} (\lambda s)^{n-1}}{(n-1)!} e^{-\lambda(t-s)} ds \quad (f_{T_n}(s) \text{ is Erlang}) \\
 &= \frac{\lambda^n e^{-\lambda t}}{(n-1)!} \int_0^t s^{n-1} ds \\
 &= \frac{(\lambda t)^n e^{-\lambda t}}{n!}
 \end{aligned}$$

□

*Remark.* By the memoryless property of  $\text{Exp}(\lambda)$ , if  $(N_t)_{t \geq 0} \sim PP(\lambda)$ , then  $(N_{t+s} - N_s)_{t \geq 0} \sim PP(\lambda)$  for all  $s \geq 0$ . Moreover,  $(N_{t+s} - N_s)_{t \geq 0}$  is independent of  $(N_\tau)_{0 \leq \tau \leq s}$ . In particular, Poisson Processes have independent and stationary increments. If  $t_0 < \dots < t_k$ , then  $(N_{t_1} - N_{t_0}), \dots, (N_{t_k} - N_{t_{k-1}})$  are independent and  $(N_{t_i} - N_{t_{i-1}}) \sim \text{Poisson}(\lambda(t_i - t_{i-1}))$  for all  $i$ .

## 5.2 Conditional Distribution of Arrivals

**Theorem 26.** *Conditioned on  $\{N_t = n\}$ ,  $(T_1, \dots, T_n) \stackrel{d}{=} (U_{(0)}, \dots, U_{(n)})$  where  $U_{(i)}$  are the order statistics of  $n$   $\text{Uniform}(0, t)$  random variables.*

In other words, given  $n$  arrivals occurred up to time  $t$ , the arrival times look like i.i.d  $\text{Unif}(0, t)$  random variables in distribution.

*Proof.* Let  $0 = t_0 \leq t_1 \leq \dots \leq t_n \leq t$ , then

$$\begin{aligned} f_{T_1 T_2 \dots T_n | N_t}(t_1 \dots t_n | n) &= \frac{\Pr\{N_t = n | T_1 = t_1, \dots, T_n = t_n\}}{\Pr\{N_t = n\}} f_{T_1 \dots T_n}(t_1 \dots t_n) \\ &= \frac{\Pr\{N_t - N_{t_n} = 0\}}{\Pr\{N_t = n\}} \prod_{i=1}^n f_{S_i}(t_i - t_{i-1}) \\ &= \frac{e^{-\lambda(t-t_n)}}{e^{-\lambda t} \frac{(\lambda t)^n}{n!}} \prod_{i=1}^n \lambda e^{-\lambda(t_i - t_{i-1})} \\ &= \frac{n!}{t^n} \text{ (density of uniform random order statistics)} \end{aligned}$$

□

## 5.3 Merging

**Theorem 27.** *If  $(N_{1,t}) \sim PP(\lambda_1)$  and  $(N_{2,t}) \sim PP(\lambda_2)$  are independent, then  $(N_{1,t} + N_{2,t}) \sim PP(\lambda_1 + \lambda_2)$ .*

*Proof.* We will show that the sum of the two independent Poisson Processes satisfies the three properties of a PP:

1.  $N_{1,0} + N_{2,0} = 0 + 0 = 0$

2. For  $0 \leq s \leq t$ ,

$$\begin{aligned} (N_{1,t} + N_{2,t}) - (N_{1,s} + N_{2,s}) &= (N_{1,t} - N_{1,s}) + (N_{2,t} - N_{2,s}) \\ &\stackrel{d}{=} \text{Poisson}(\lambda_1(t-s)) * \text{Poisson}(\lambda_2(t-s)) \\ &= \text{Poisson}((\lambda_1 + \lambda_2)(t-s)) \end{aligned}$$

3.  $(N_{1,t} + N_{2,t})_{t \geq 0}$  has independent increments since  $(N_{1,t})_{t \geq 0}$ ,  $(N_{2,t})_{t \geq 0}$  has independent increments.

□

## 5.4 Splitting (a.k.a Thinning)

**Theorem 28.** *Let  $p_1, \dots, p_k$  be non-negative such that  $\sum_{i=1}^k p_i = 1$  and  $(N_t)_{t \geq 0}$  be a  $PP(\lambda)$ . Mark each arrival with label "i" with probability  $p_i$ , independently of all other arrivals so that  $(N_{i,t})_{t \geq 0}$  be the process that counts arrivals marked with "i". Then  $(N_{i,t})_{t \geq 0}$ , for  $i = 1, \dots, k$ , are independent Poisson Processes with respective rates  $p_i \lambda$  for  $i = 1, \dots, k$ .*

*Proof.* We will only prove for  $k = 2$ . This is sufficient because we can simply do induction to get  $k > 2$ . For  $k = 2$ , we let  $p_1 = p$  and  $p_2 = 1 - p$ .

$$\begin{aligned}
Pr\{N_{1,t} = n, N_{2,t} = m\} &= Pr\{N_{1,t} = n, N_{2,t} = m, N_t = n + m\} \\
&= Pr\{N_{1,t} = n, N_{2,t} = m | N_t = n + m\} Pr\{N_t = n + m\} \\
&= \binom{n+m}{n} p^n (1-p)^m e^{-\lambda t} \frac{(\lambda t)^{n+m}}{(n+m)!} \\
&= e^{(-p\lambda)t} \frac{(p\lambda t)^n}{n!} e^{(-(1-p)\lambda)t} \frac{((1-p)\lambda t)^m}{m!} \\
&= \text{Poisson}(p\lambda t) \text{Poisson}((1-p)\lambda t)
\end{aligned}$$

□

## 5.5 Random Incidence Paradox

Consider  $(N_t)_{t \geq 0} \sim PP(\lambda)$  and pick a random time  $t_0$ . What is the expected length of the inter-arrival interval in which  $t_0$  falls?

Say it falls between  $T_i$  and  $T_{i+1}$ . Then the length of the inter-arrival interval is  $L = (t_0 - T_i) + (T_{i+1} - t_0)$ . We know that  $T_{i+1} - t_0 \sim \text{Exp}(\lambda)$  by the memoryless property of the exponential distribution. We also know that

$$Pr(t_0 - T_i > s) = Pr(\text{no arrivals in } (t_0 - s, s)) = Pr(N_{t_0} - N_{t_0-s} = 0) = e^{-\lambda s}$$

so  $t_0 - T_i \sim \text{Exp}(\lambda)$ . By linearity of expectation,  $\mathbb{E}[L] = \frac{2}{\lambda}$ . If we arrive at a random time, we are more likely to land in a long interval.



## 6 Continuous Time Markov Chains (CTMCs)

### 6.1 Construction

Intuitively, a CTMC is a markov chain where we need to wait for  $\text{Exp}(\lambda)$  time before transitioning to the next state.

**Definition 6.1** (CTMC). Let  $S$  be a countable state space. A CTMC is defined in terms of a rate matrix  $Q$  satisfying  $[Q]_{ij} \geq 0$  for  $i \neq j$ ,  $i, j \in S$  and  $\sum_{j \in S} [Q]_{ij} = 0$  for all  $i \in S$ . Specifically, the transition rate for state  $i$  is  $q_i := [Q]_{ii} = -\sum_{j \neq i} [Q]_{ij}$ . We also have  $[Q]_{ij} = q_i p_{ij}$  such that  $\sum_{j \in S} p_{ij} = 1$  where  $p_{ii} = 0$  and  $p_{ij} \geq 0$ .  $p_{ij}$  are the transition probabilities for an associated DTMC called the jump chain.

A CTMC with rate matrix  $Q$  works as followed:

1. Start with  $X_0 = i$ .
2. Hold for  $\text{Exp}(q_i)$  amount of time, then jump to state  $j \in S$  with probability  $p_{ij}$  where  $j \in S$ .
3. Repeatedly apply the previous line above at next states (starting at state  $j$ ).

We can equivalently define CTMCs by their jump rates  $q_{ij}$ . On entering state  $i$ , consider independent random variables  $T_j \sim \text{Exp}(q_{ij})$  for  $j \in S \setminus \{i\}$  and jump to state  $j^* = \text{argmin}_{j \in S} (T_j : j \in S)$  at time  $T_{j^*}$ . This valid due to the splitting property of Poisson Processes.

*Remark.* This is called a markov chain by the memoryless property of the exponential distribution:

$$\Pr(X_{t+\tau} = j | X_t = i, X_s = i_s, 0 \leq s < t) = \Pr(X_{t+\tau} | X_t = i)$$

### 6.2 Stationary Distributions

**Definition 6.2** (CTMC Stationarity). A probability vector  $\pi$  is (without considering pathological cases) a stationary distribution for a CTMC with rate matrix  $Q$  if  $\pi Q = 0$ . This called the rate conservation principle. This is equivalent to  $\pi_j q_j = \sum_{i \in S} \pi_i q_{ij}$  for all  $j \in S$ . In other words, assuming that  $\Pr(X_t = i) = \pi_i$ , the rate at which transitions are made out of  $j$  is equal to the rate at which transitions are made into  $j$ .

### 6.3 Classification of States

Similar to DTMCs, we can classify the states.

- We say  $i$  and  $j$  communicate (i.e.  $i \leftrightarrow j$ ) iff  $i \leftrightarrow j$  is a jump chain iff we can travel  $i \rightarrow j$  and back.

- Classes in CTMC are same as those in associated jump chain.
- State  $j$  is transient if, given  $X_0 = j$ ,  $(X_t)_{t \geq 0}$  re-enters state  $j$  finitely many times with probability one. State  $j$  is recurrent otherwise.
- For a recurrent state  $j$ , define  $T_j = \min\{t \geq 0 : X_t = j \text{ and } X_s \neq j \text{ for some } s < t\}$ .
- State  $j$  is positive recurrent if  $\mathbb{E}[T_j | X_0 = j] < \infty$ .
- State  $j$  is null recurrent if  $\mathbb{E}[T_j | X_0 = j] = \infty$ .
- Transience/Positive Recurrence/Null Recurrence are class properties
- There is no concept of periodicity.

## 6.4 Big Theorem

**Theorem 29.** We define  $P_{ij}^t := \Pr(X_t = j | X_0 = i)$  and  $m_j := \mathbb{E}[T_j | X_0 = j]$ . For an irreducible CTMC, exactly one of the following is true:

1. Either all states are transient or all states are null recurrent. In this case, no stationary distribution exists, and  $\lim_{t \rightarrow \infty} P_{ij}^t = 0$  for all  $i, j \in S$ .
2. All states are positive recurrent. In this case, a unique stationary distribution exists and satisfies  $\pi_j = \frac{1}{m_j q_j} = \lim_{t \rightarrow \infty} P_{ij}^t$  for all  $i, j \in S$ .

*Remark.* Stationary distribution in CTMC is not the same as the stationary distribution in the jump chain. Generally speaking,  $\tilde{\pi}_j = \frac{\pi_j q_j}{\sum_{i \in S} \pi_i q_i}$  given that  $\sum_{i \in S} \pi_i q_i < \infty$  where  $\tilde{\pi}_j$  is the stationary distribution of the jump chain. Equivalently,  $\pi_i = \frac{\frac{1}{q_i} \tilde{\pi}_i}{\sum_{j \in S} \frac{1}{q_j} \tilde{\pi}_j}$ .

## 6.5 Examples

### 6.5.1 M/M/s queue

Customers arrive to a system with  $s$  servers according to  $PP(\lambda)$ . If a server is available, the arrival is immediately serviced, which takes  $\overset{IID}{\sim} \text{Exp}(\mu)$ . If no server is available, the arrival waits until one becomes available. Let  $(X_t)_{t \geq 0}$  denote the number of customers in system at time  $t \geq 0$ . We can model this

$$\text{with } q_{n,n+1} = \lambda \text{ and } q_{n,n-1} = \begin{cases} n\mu & 1 \leq n \leq s \\ s\mu & n > s \end{cases}.$$

### 6.5.2 Birth Death Chain

Individuals give birth  $\overset{IID}{\sim} PP(\lambda)$  and have lifetimes  $\overset{IID}{\sim} \text{Exp}(\mu)$ . Let  $X_t$  be the number of individuals in population at time  $t$ . We can model this with  $q_{n,n+1} = n\lambda$  and  $q_{n,n-1} = n\mu$ . Note that this means  $q_n = n(\lambda + \mu)$  so then  $p_{n,n+1} = \frac{\lambda}{\lambda + \mu}$  and  $p_{n,n-1} = \frac{\mu}{\lambda + \mu}$ , so the DT jump chain is also a birth-death chain.

### 6.5.3 M/M/ $\infty$ queue

This is the same of the M/M/s queue problem except there are infinite servers. In this case  $q_{n,n+1} = \lambda$  and  $q_{n,n-1} = n\mu$ . If we solve  $\pi Q = 0$ , we see that  $\pi_n = \frac{e^{-\lambda/\mu}(\lambda/\mu)^n}{n!}$ . By the Big Theorem,  $X_t \xrightarrow{d} \text{Poisson}(\lambda/\mu)$  where  $X_t$  is the number of people in the system at time t.

## 6.6 First Step Equations (FSE)

If  $A \subseteq S$ , define  $T_A = \min_t \{t \geq 0 : X_t \in A\}$ . We want to compute  $\mathbb{E}[T_A | X_0 = i]$ , so we will use FSEs to do this. Define  $t_i := \mathbb{E}[T_A | X_0 = i]$  and  $t_i = 0 \ \forall i \in A$ . Then we want to if  $t_i = \mathbb{E}[\text{hold time}] + \sum p_{ij} t_j \ \forall i \in S$ . Thus our FSEs are

$$\begin{aligned} t_i &= 0 \quad \forall i \in A \\ t_i &= \frac{1}{q_i} + \sum_{j \in S} p_{ij} t_j \quad \forall i \notin A \end{aligned}$$

## 6.7 Uniformization

Uniformization is an approach to compute CTMC transition probabilities by simulating a DTMC.

### 6.7.1 Context

For context, consider a CTMC with transition rates  $(q_i)_{i \in S}$  and assume  $\exists M > 0$  s.t.  $q_i \leq M \ \forall i \in S$ . We want to find  $P_t$  for some  $t \geq 0$ . Here,

$$[P_t]_{ij} := \Pr(X_t = j | x_0 = i)$$

Markovity gives the Chapman-Kolmogorov Equations, which is  $P^{s+t} = P^s P^t \ \forall s, t \geq 0$ . We can also show that for  $h \approx 0$ ,  $P^h \approx I + hQ + O(h)$  so

$$\begin{aligned} P^{t+h} &= P^t P^h \\ &\approx P^t (I + hQ + O(h)) \\ \frac{P^{t+h} - P^t}{h} &= P^t Q + \frac{O(h)}{h} \\ \frac{\partial}{\partial t} P^t &= P^t Q \\ P^t &= e^{tQ} := \sum_{k \geq 0} \frac{(tQ)^k}{k!} \quad \forall t \geq 0 \end{aligned}$$

So we've found a way to compute  $P^t$ , but this becomes intractable for large state spaces. This is where uniformization comes in.

### 6.7.2 Construction

Let us define a uniformized DTMC which is a DTMC, given  $\gamma \geq M$ , with transition probabilities

$$p_{ij} = \frac{q_{ij}}{\gamma} \quad p_{ii} = 1 - \frac{q_i}{\gamma} \quad i, j \in S$$

If  $P_u$  = transition matrix with uniformed DTMC, then  $P_u = I + \frac{1}{\gamma}Q$ . So observe  $\pi P_u = \pi + \frac{1}{\gamma}\pi Q$ . In other words,  $\pi P_u = \pi \iff \pi Q = 0 \iff \pi$  is a stationary distribution for both the CTMC and uniformized DTMC. So we're beginning to see that the behavior of the two chains are similar. In fact, we can see that

$$P_u^n = (I + \frac{1}{\gamma}Q)^n \approx e^{\frac{n}{\gamma}Q}$$

So to estimate  $P^t$ , we can run the uniformized DTMC for  $n \approx \gamma t$  steps because  $P^t = e^{tQ} \approx e^{\frac{n}{\gamma}Q} \approx P_u^n$ . Notice that with a larger  $\gamma$ , we get a better approximation.

## 7 Random Graphs

### 7.1 Definition

**Definition 7.1** (Erdős–Rényi Random Graphs). Fix  $n \geq 1$  and  $p \in [0, 1]$ . A random graph  $G(n, p)$  is an undirected graph on  $n$  vertices, where each edge is placed independently with probability  $p$ .

### 7.2 Thresholds

The flavor of results around random graphs are threshold results (aka phase transitions).

#### 7.2.1 Existence of Edges

An example is if  $p \gg \frac{1}{n^2}$  then graph has edges with high probability but if  $p \ll \frac{1}{n^2}$  then graph doesn't have edges with high probability. To prove this, let  $X = \#$  of edges in  $G(n, p_n)$  and take  $p_n = \frac{c}{n^2}$ . Note that  $X \sim \text{Binomial}(\binom{n}{2}, p_n)$ . So  $P(X = 0) = (1 - p_n)^{\binom{n}{2}} \rightarrow e^{-c/2}$ . So if  $c \gg 1$ ,  $P(X = 0) \approx 0$  and if  $c \ll 1$ ,  $P(X = 0) \approx 1$ .

#### 7.2.2 Existence of Cycles

If  $p \gg \frac{1}{n}$ , there exists a cycle whp. If  $p \ll \frac{1}{n}$ , there doesn't exist a cycle whp.

#### 7.2.3 Largest Connected Components

If  $p \gg \frac{1}{n}$ , the largest connected component is of size  $\Theta(n)$ . If  $p \ll \frac{1}{n}$ , the largest connected component is of size  $O(\log n)$ .

#### 7.2.4 Connectivity

**Lemma 1.**  $P(X = 0) \leq \frac{\text{Var}(X)}{(\mathbb{E}[X])^2}$

*Proof.*

$$\begin{aligned} \text{Var}(X) &= P(X = 0)\mathbb{E}[(X - \mathbb{E}(X))^2 | X = 0] + P(X \neq 0)\mathbb{E}[(X - \mathbb{E}(X))^2 | X \neq 0] \\ &\geq P(X = 0)(\mathbb{E}[X])^2 \end{aligned}$$

□

**Theorem 30** (Erdős–Rényi). Fix  $\lambda > 0$ , and let  $p_n = \lambda \frac{\log n}{n}$ . If  $\lambda > 1$ , then  $P(G(n, p_n) \text{ is connected}) \rightarrow 1$ . If  $\lambda < 1$ , then  $P(G(n, p_n) \text{ is connected}) \rightarrow 0$ .

*Proof.* When  $\lambda < 1$ , let  $X$  = number of isolated vertices. We want to show that  $P(X = 0) \rightarrow 0$ . Let  $I_i$  be the indicator that vertex  $i$  is isolated. Then

$$\mathbb{E}[X] = n\mathbb{E}[I_i] = n(1 - p)^{n-1} := nq$$

$$Var(X) = \sum Var(I_i) + \sum_{i \neq j} Cov(I_i, I_j) = nq(1-q) + n(n-1) \frac{pq^2}{1-p}$$

So  $P(X = 0) \leq \frac{nq(1-q) + n(n-1) \frac{pq^2}{1-p}}{n^2 q^2} = \frac{1-q}{nq} + \frac{p}{1-p} \leq \frac{1}{nq} + \frac{p}{1-p} \rightarrow 0$  as  $p$  goes to 0 and  $n$  goes to infinity.  $\frac{1}{nq}$  converges to 0 because  $\log(nq) = \log(n) + (n-1)\log(1-p) \approx \log(n) - (n-1)p = \log(n^{1-\lambda}) \rightarrow \infty$  since  $\lambda < 1$ .

When  $\lambda > 1$ ,

$$\begin{aligned} P(G(n, p) \text{ is disconnected}) &= P(\cup_{k=1}^{n/2} \{\text{exists set of } k \text{ disconnected vertices}\}) \\ &\leq \sum_{k=1}^{n/2} \binom{n}{k} (1-p)^{k(n-k)} \\ &\rightarrow 0 \text{ for } \lambda > 1 \end{aligned}$$

□

## 8 Statistical Inference

### 8.1 MAP/MLE

Let  $X$  be the state of nature that takes values in  $\{0, \dots, M-1\}$  (i.e.  $M$  hypotheses to consider), and  $Y$  be the observation. Then the model is represented by likelihoods  $p_{Y|X}(y|x)$ . We will be doing bayesian inference, so we are assuming that  $X$  is a random variable with a known distribution  $P(X = i) = \pi_i$ . We call  $\pi$  the prior.

#### 8.1.1 Maximum A Posteriori (MAP)

If we observe  $\{Y = y\}$ , then the a posteriori probability of  $\{X = x\}$  is given by:

$$P(X = x|Y = y) = \frac{p_{Y|X}(y|x)\pi(x)}{\sum_{\tilde{x}} p_{Y|X}(y|\tilde{x})\pi(\tilde{x})} \propto p_{Y|X}(y|x)\pi(x)$$

The idea is that our prior has been updated given observations. This motivates MAP.

$$\hat{X}_{MAP}(y) = \operatorname{argmax}_x p_{Y|X}(y|x)\pi(x) = \operatorname{argmax}_x p_{X|Y}(x|y)$$

MAP estimate depends on likelihoods and prior. What if we don't have a prior though? Then let us assume that  $\pi$  is uniform over all  $x$ . This gives rise to maximum likelihood estimate (ML):

$$\hat{X}_{ML}(y) = \operatorname{argmax}_x p_{Y|X}(y|x)$$