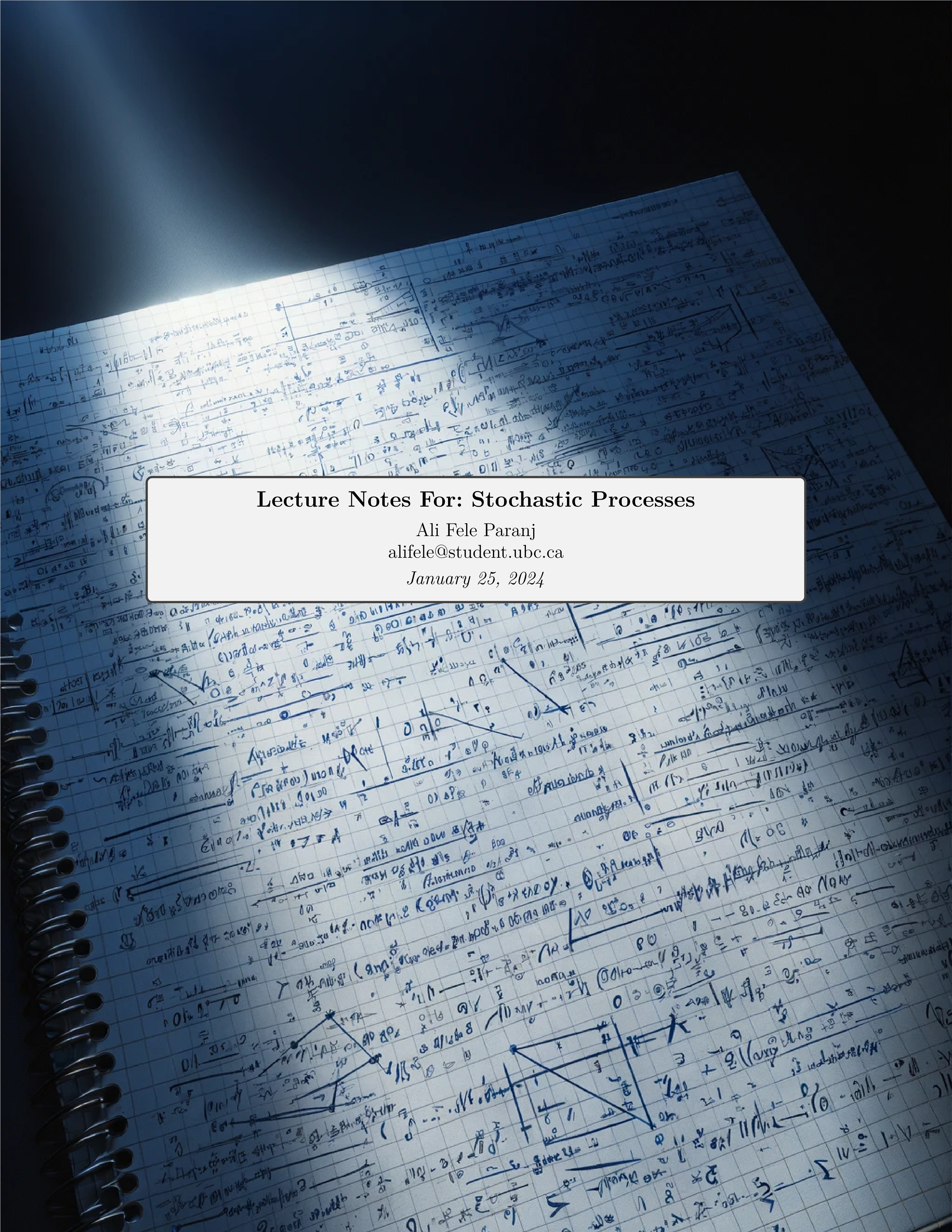

Lecture Notes For: Stochastic Processes

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0. Contents

1. Basics and Definitions

1.1 Solved Problems

■ **Problem 1.1 — From Ross.** Ben can talk a course in compute science or chemistry. If she takes the computer science course, then she will get A grade with probability $\frac{1}{2}$. If she takes the chemistry course, then she will get A grade with probability $\frac{1}{3}$. She decides to base her decision on the flip of a fair coin. What is the probability that she gets an A in chemistry?

Solution We define the following events

A: she will get an A grade.
CO: she will take the computer science course.
CH: she will take the chemistry course.

Then the question is basically asking for $\mathbb{P}(A \cap CH)$. We can compute it by

$$\mathbb{P}(A \cap CH) = \mathbb{P}(A|CH)\mathbb{P}(CH) = \frac{1}{3} \cdot \frac{1}{2} = \frac{1}{6}.$$

■ **Problem 1.2** And urn contains seven black balls and five white balls. We draw two times from the urn. Given that the each ball has the same probability to be drawn, what is the probability that both balls drawn are black?

Solution This question nicely demonstrates the fact that there are many ways to define the event spaces, and not all of them are very useful in computing the desired probability. Define

E: two drawn balls are black.

The question is in fact asking $\mathbb{P}(E)$. But this even is not very useful in any progress with the solution. Thus we need to define some finer events

E_1: The first drawn ball is black.
E_2: The second drawn ball is black.

It is clear that $E = E_1 \cap E_2$. These two finer events allows us to compute the probability of interest given the data we have in our hand.

$$\mathbb{P}(E_1 \cap E_2) = \mathbb{P}(E_2|E_1)\mathbb{P}(E_1) = \frac{6}{11} \cdot \frac{7}{12}$$

■ **Problem 1.3 — From Ross.** Three men at a party through their hats into the center of the room, and then, after mixing the hats, each pick a hat randomly. What is the probability if non of them get their own hat back.

Solution There are a million ways to tack a probability problem. We can construct a suitable sample space and then compute the probabilities explicitly, or we can use the properties of the probability function to computer the desired probability without any need to construct the sample space. Here, we will demonstrate two ways.

Solving the problem by utilizing the properties of the probability function. First we need to define some suitable events. There are again many ways to define event sets and each have their own pros and cons. We proceed with the following definition.

E_i: The person i "selects" his own hat.

Also, with this particular construction of the event sets, it is much more easier to compute the complementary probability of the desired probability first and then compute the desired one by simply subtracting it from 1. The complement of the event "no men gets his own hat back" is "at least one man gets his hat back" which is $\mathbb{P}(E_1 \cup E_2 \cup E_3)$. To compute the terms of this we first need to calculate $\mathbb{P}(E_i)$, $\mathbb{P}(E_i \cap E_j)$ where $i \neq j$ and also $\mathbb{P}(E_1 \cap E_2 \cap E_3)$. We know that $\mathbb{P}(E_i) = 1/3$ for $i = 1, 2, 3$. That is because it is equally likely he selects any of the hats at the center. For $\mathbb{P}(E_i \cap E_j)$ we can write

$$\mathbb{P}(E_i \cap E_j) = \mathbb{P}(E_i|E_j)\mathbb{P}(E_j) = \frac{1}{2} \cdot \frac{1}{3} = \frac{1}{6}.$$

In which we used the fact that $\mathbb{P}(E_i|E_j)$ is $\frac{1}{2}$ for distinct i, j. That is because given person j selects his hat correctly, then there are two possibilities for E_i to select his hat (he can pick the correct one or the wrong one). Lastly for $\mathbb{P}(E_1 \cap E_2 \cap E_3)$ we write

$$\mathbb{P}(E_1 \cap E_2 \cap E_3) = \mathbb{P}(E_1|E_2 \cap E_3)\mathbb{P}(E_2 \cap E_3) = \mathbb{P}(E_1|E_2 \cap E_3)\mathbb{P}(E_2|E_3)\mathbb{P}(E_3) = 1 \cdot \frac{1}{2} \cdot \frac{1}{3} = \frac{1}{6}.$$

Thus

$$\mathbb{P}(E_1 \cup E_2 \cup E_3) = (1) - (1/2) + (1/6) = \frac{4}{6}.$$

Then the probability of interest will be

$$\mathbb{P}(E) = 1 - \frac{4}{6} = \frac{1}{3}.$$

Solving by constructing a sample space. A suitable sample space for this problem can be the set of all permutations on three letters. This set is

$$\Omega = \{\begin{pmatrix} a & b & c \\ \boxed{a} & \boxed{b} & \boxed{c} \end{pmatrix}, \begin{pmatrix} a & b & c \\ \boxed{a} & c & b \end{pmatrix}, \begin{pmatrix} a & b & c \\ b & a & \boxed{c} \end{pmatrix}, \begin{pmatrix} a & b & c \\ b & c & a \end{pmatrix}, \begin{pmatrix} a & b & c \\ c & a & b \end{pmatrix}, \begin{pmatrix} a & b & c \\ c & \boxed{b} & a \end{pmatrix}\}.$$

Note that the elements in the box represents the fixed point of the permutation. The probability of interest is basically the number of permutations that has no fixed point. As it is clear from the set Ω, the probability is

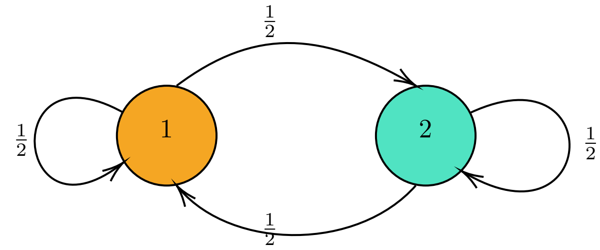
$$\mathbb{P}(E) = \frac{2}{6} = \frac{1}{3}.$$

2. Markov Chain

Notation Let $(X_n)_{n\geq 0}$ be a Markov chain on the state space S, $x \in S$, and let E be an event. Then

$$\mathbb{P}_x(E) = \mathbb{P}(E|X_0 = x).$$

■ **Example 2.1** It is a good practice to derive the value of the transition probability of a simple Markov chain using the first principles. Consider the Markov chain representing a lamp that turns on with probability 1/2 and turns off with probability 1/2, and stays at the old state with probability 1/2. Thus we will have the following diagram for this Markov chain.



In this example, the state space is $S = \{0, 1\}$, and the sample space is

$$\Omega = \{(x_1, x_2, \cdots) : x_i \in S\}$$

which is basically the set of all sequences of one's and zero's. Given this, the random variables $(X_n)_n$ defined t be

$$X_n(\omega) = x_n,$$

where $\omega \in \Omega$ and x_n is the n-th letter in ω. Intuitively speaking, we know that

$$P(1, 0) = \mathbb{P}(X_{n+1} = 1|X_n = 0) = \frac{1}{2}.$$

However, here we want to derive that number more explicitly by working directly with the elements of the probability space. First, we need to determine the event associated with $X_{n+1} = 1$. This is the event that has elements where the $n+1$-th position is 1. I.e.

$$E = \{(x_1, x_2, \cdots, x_n, 1, x_{n+2}, \cdots) : x_i \in S\}.$$

Similarly, we have

$$F = \{(x_1, x_2, \cdots, x_{n-1}, 0, x_{n+1}, \cdots) : x_i \in S\}.$$

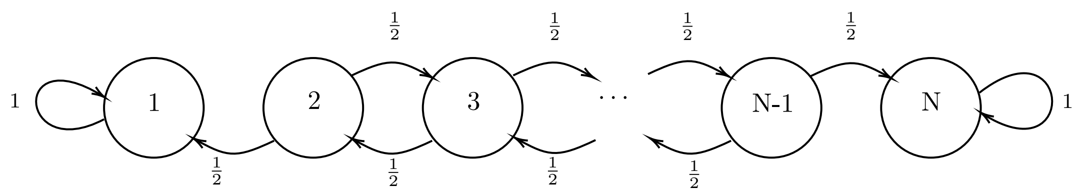
So we have

$$\mathbb{P}(X_{n+1} = 1 | X_n = 0) = \mathbb{P}(E|F) = \frac{\mathbb{P}(E \cap F)}{\mathbb{P}(F)} = \frac{\mathbb{P}(E \cap F)}{\mathbb{P}(F \cap E) + \mathbb{P}(F \cap E^c)} = \frac{\frac{1}{|\Omega|}}{\frac{1}{|\Omega|} + \frac{1}{|\Omega|}} = \frac{1}{2}.$$

Note that $\mathbb{P}(E \cap F) = \frac{1}{|\Omega|}$, since out of many combinations of the sequence of zeros and ones, there is one one sequence whose n-th place is 0 and $n+1$-th place is 1. Furthermore, $\mathbb{P}(F \cap E^c) = \frac{1}{|\Omega|}$ as there is only one string where its n-th and $(n+1)$-th string are both zero. ■

■ **Example 2.2 — Gambler's Ruin.** Suppose Alice and Bob have in total of N coins. Alice and Bob play a game with a fair coin. When Alice wins, gets a coin from Bop, and vise versa. What is the probability that Alice wins if she starts with $0 \le a \le N$ coins.

Solution There are many ways to tackle a probability problem like this and the solution presented here is not the only way to find the solution to this problem. We want to model this with Markov chain whose state space is $\{0, 1, 2, \cdots, N\}$. Thus X_n represents the fortune of Alice after playing the games for n times.



Let p_a be the probability of Alice wining if she starts with a coins. First, observe that $p_0 = 0$ and $p_N = 1$. Let E denote that event of Alice wining the whole game. Also, let F_1 be the event in which she looses the first game and F_2 the event in which she wins the first game. Then

$$p_a = \mathbb{P}_a(E) = \underbrace{\mathbb{P}_a(E|F_1)}_{\mathbb{P}(E|F_1, X_0 = a)} \mathbb{P}(F_1) + \underbrace{\mathbb{P}_a(E|F_1^c)}_{\mathbb{P}(E|F_1^c, X_0 = a)} \mathbb{P}(F_1^c)$$

(note that this identity is actually true for any set F_1, but here F_1 is the specific event explained above). The probability that she looses or wins the first game is $\frac{1}{2}$. Also, observe that $\mathbb{P}_a(E|F_1) = p_{a+1}$ (since if she wins the first game she will have one more coin) and $\mathbb{P}_a(E|F_1^c) = p_{a-1}$. Thus

$$p_a = \frac{1}{2} p_{a+1} + \frac{1}{2} p_{a-1}.$$

Now we can solve this recurrent equation with the characterization polynomial which is $2 = X + 1/X$ or $X^2 - 2X + 1 = (X-1)^2 = 0$. Thus the characteristic polynomial has a double root. Thus

$$p_a = (Aa + B)(1)^a = Aa + B.$$

Since $p_0 = 0, \; p_N = 1$, then it turns out that

$$p_a = \frac{a}{N}.$$

■

■ **Example 2.3 — Gambler's Ruin with Draw.** Let Alice and Bob play Rock-Paper-Scissors. If Alice and Bob has a total of N coins, and at each play, the winner gets one coin from the loser, what is the probability that Alice will win the game if he starts with a coins. When they draw, then they repeat the game (or equivalently, they play another game without any coins exchange).

Solution We need to do a first step analysis similar to what we did before. Let E be the event that Alice wins the whole game, and the event $F = F_{-1} \cup F_0 \cup F_1$ where

F_{-1}: Alice loses the first game,
F_0: Alice draws the first game,
F_1: Alice wins the first game.

It is clear that $\mathbb{P}(F) = 1$, since the components are mutually disjoint. Thus $E \cap F_{-1}$, $E \cap F_0$, $E \cap F_1$ are also mutually disjoints where. Thus we can write

$$\mathbb{P}_a(E) = \mathbb{P}_a(E \cap F_{-1}) + \mathbb{P}_a(E \cap F_0) + \mathbb{P}_a(E \cap F_1) = \mathbb{P}_a(E|F_{-1})\mathbb{P}_a(F_{-1}) + \mathbb{P}_a(E|F_0)\mathbb{P}_a(F_0) + \mathbb{P}_a(E|F_1)\mathbb{P}_a(F_1).$$

Since the game is fair we know

$$\mathbb{P}_a(F_{-1}) = \mathbb{P}_a(F_0) = \mathbb{P}_a(F_1) = \frac{1}{3}.$$

Furthermore, we know

$$\mathbb{P}_a(E|F_{-1}) = p_{a-1}, \qquad \mathbb{P}_a(E|F_0) = p_a, \qquad \mathbb{P}_a(E|F_1) = p_{a+1}.$$

Thus the first step analysis will lead to the following identity.

$$\mathbb{P}_a(E) = p_a = \frac{1}{3}(p_{a-1} + p_a + p_{a+1}),$$

which after simplification becomes

$$2p_a = p_{a-1} + p_{a+1},$$

which is the same recursive formula we got in the previous example. So the possibility of the draw, will not change the behaviour of the system.

■

Proposition 2.1 — First step argument. Let $(X_n)_{n\geq 0}$ be a Markov chain on the state space S. Let $x \in S$, and $W, Z \subset S$. Let B be any event. Then

$$\mathbb{P}_x(B) = \sum_{y:x\sim y} \mathbb{P}_y(B)P(x,y).$$

Proof. To prove the proposition above, we Let $E_i = \{X_0 = x, X_1 = y_i\}$ where $y_i \sim x$. So, in words, we say that the event E_i has occurred if $X_1 = y_i$. It is clear that $E_i \cap E_j = \varnothing$ where $i \neq j$. Thus $\bigcup_i (B \cap E_i) = B$. Thus

$$\mathbb{P}_x(B) = \sum_i \mathbb{P}_x(B \cap E_i) = \sum_i \mathbb{P}_x(B|E_i)\mathbb{P}_x(E_i).$$

In which $\mathbb{P}_x(E_i) = \mathbb{P}(E_i|X_0 = x) = \mathbb{P}(X_1 = y_i|X_0 = x) = P(x, y_i)$. Also

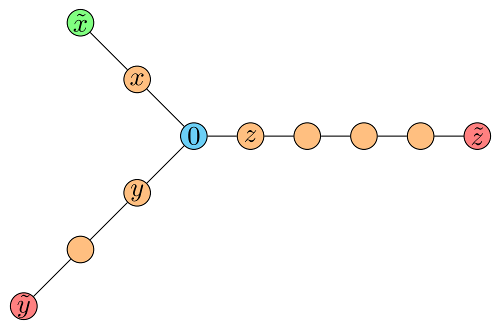
$$\mathbb{P}_x(B|E_i) = \mathbb{P}(B|X_1 = y_i, X_0 = x) = \mathbb{P}(B|X_1 = y_i) = \mathbb{P}_{y_i}(B),$$

. in which we have used the Markov property. Thus we can write

$$P_x(B) = \sum_i \mathbb{P}_{y_i}(B)P(x, y_i).$$

□

■ **Example 2.4** Consider the a simple random walker on the following graph. Let $B = \{T_{\tilde{x}} < T_{\{\tilde{z},\tilde{y}\}}\}$. Compute the probability $\mathbb{P}_0(B)$.



Solution This problem is simply asking what is the probability that we hit $\tilde{x}$ state before hitting any of $\tilde{y}$ or $\tilde{z}$ states, given the fact that the random walker starts from the state 0. To keep unnecessary details out of the way, we have only labeled the vertices that we will use in our analysis. We will have the following notation to simplify the solution

$$p_v = \mathbb{P}_v(B),$$

where v is any vertex in the graph. Note that starting at 0, i.e. $X_0 = 0$, then going to any of the states x, y, or z, are mutually disjoint events, and the probability of the union of these events is one. With our first time step analysis (see Proposition 2.1) we can write

$$\mathbb{P}_0(B) = \frac{1}{3}(p_x + p_y + p_z).$$

Now we need to analyze each of terms in the RHS. Let's start with p_z. Consider two events $\{T_0 < T_{\tilde{z}}\}$ and $\{T_0 > T_{\tilde{z}}\}$, where the first time is the event where the random walker hits the 0 state before hitting the $\tilde{z}$ step first, and the second one is the vice versa. These two events are disjoint and the probability of the union is 1. Thus we write the conditional expansion of p_z based on these events

$$p_z = \mathbb{P}_z(B) = \mathbb{P}_z(B|T_0 < T_{\tilde{z}})\mathbb{P}_z(T_0 < T_{\tilde{z}}) + \mathbb{P}_z(B|T_0 > T_{\tilde{z}})\mathbb{P}_z(T_0 > T_{\tilde{z}}).$$

We know that $\mathbb{P}_z(B|T_0 > T_{\tilde{z}}) = \mathbb{P}(B|X_0 = z, X_i = \tilde{z})$ for some $i > 0$. From Markov property it follows that

$$\mathbb{P}(B|X_0 = z, X_i = \tilde{z}) = \mathbb{P}(B|X_i = \tilde{z}) = \mathbb{P}(B|X_0 = \tilde{z}) = p_{\tilde{z}}.$$

Also $\mathbb{P}_z(B|T_0 < T_{\tilde{z}}) = \mathbb{P}_0(B) = p_0$ by the Markov property. Lastly, $\mathbb{P}_z(T_0 < T_{\tilde{z}})$ is determined by the Gambler's ruin method we say before, which is basically

$$\mathbb{P}_z(T_0 < T_{\tilde{z}}) = \frac{5}{4}, \qquad \mathbb{P}_z(T_0 > T_{\tilde{z}}) = \frac{1}{5}.$$

By doing the same kind of analysis for p_x as well as p_y we will get

$$p_z = \frac{4}{5}p_0, \qquad p_y = \frac{2}{3}p_0, \qquad p_x = \frac{1}{2}p_0 + \frac{1}{2}.$$

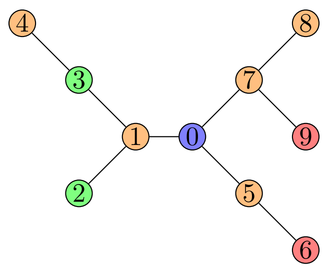
Now by substituting in the identity we got from the first time step argument, we can fine that

$$p_0 = \frac{15}{31},$$

And this completes our solution for the problem.

■

■ **Example 2.5** Consider the graph $\gamma = (V, E)$ drawn below. Set $Z = \{2, 3\}$, and $W = \{6, 9\}$. Compute $\mathbb{P}_0(T_Z < T_W)$. In colors: we start at blue, win if we reach green, and lose of we reach red.



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Solution As always, we start with our powerful tool in hand, which is the first step argument (which is basically a special form of the more general conditional expansion). We start with first step argument at state 0. We will get

$$\mathbb{P}_0(B) = \frac{1}{3}(\mathbb{P}_1(B) + \mathbb{P}_7(B) + \mathbb{P}_5(B)),$$

and now we need to analyze each of the terms in the right hand side. We start with $\mathbb{P}_5(B)$ which is the most straight forward one. As we saw in the last example, we can analyze this state with a conditional expansion on the two disjoint events, whose union probability is 1. Let those two events be $\{T_6 < T_0\}$ (where the random walker hits the state 6 before hitting the state 0), and $\{T_6 > T_0\}$, where the random walker hits the state 0 before hitting the state 6. Thus the expansion will be

$$\mathbb{P}_5(B) = \mathbb{P}_5(B|T_6 < T_0)\mathbb{P}_5(T_6 < T_0) + \mathbb{P}_5(B|T_6 > T_0)\mathbb{P}_5(T_6 > T_0).$$

We know that if we hit the state 6 before 0, we have no chance to hit any of the green states (we will lose). Thus

$$\mathbb{P}_5(B|T_6 < T_0) = 0.$$

And from the Gambler's ruin we know that $\mathbb{P}_5(T_6 > T_0) = 1/2$, and from the Markov property we know that $\mathbb{P}_5(B|T_6 > T_0) = \mathbb{P}_0(B)$, because the conditional probability $\mathbb{P}_5(B|T_6 > T_0)$ is basically stating what is the probability of B happening, if we start from 5 and $X_i = 0$ for some i in the future. Thus

$$\mathbb{P}_5(B) = \frac{\mathbb{P}_0(B)}{2}.$$

Now, we need to analyze the term $\mathbb{P}_1(B)$. Again, at this step, we do another first step analysis.

$$\mathbb{P}_1(B) = \frac{1}{3}(\underbrace{\mathbb{P}_3(B)}_{=1} + \underbrace{\mathbb{P}_2(B)}_{=1} + \mathbb{P}_0(B)) = \frac{2 + \mathbb{P}_0(B)}{3}.$$

Note that from the assumption, we know that if we reach any of green states, then we are declared winner, that is why we have $\mathbb{P}_3(B) = \mathbb{P}_2(B) = 1$. Now it only remains to analyze the term $\mathbb{P}_7(B)$. Again, similar to the case above, we do a first time step argument

$$\mathbb{P}_7(B) = \frac{1}{3}(\mathbb{P}_0(B) + \underbrace{\mathbb{P}_8(B)}_{=\mathbb{P}_7(B)} + \underbrace{\mathbb{P}_9(B)}_{=0}) \implies \mathbb{P}_7(B) = \frac{\mathbb{P}_0(B)}{2}.$$

Note that $\mathbb{P}_8(B) = \mathbb{P}_7(B)$ by a first stem analysis when starting at the state 8. Putting all of these terms back to the original identity we derived the first, we can conclude that

$$p_0 = \mathbb{P}_0(B) = \frac{2}{5}.$$