

STA447

Lecture Notes

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1 Preliminary

Theorem 1.1 (Dominated Convergence Theorem). If $\lim_{n \rightarrow \infty} X_n = X$, and there is some random variable Y with $E|Y| < \infty$ and $|X_n| \leq Y$ for all n , then

$$\lim_{n \rightarrow \infty} E(X_n) = E(X)$$

2 Markov Chain Probabilities

Notation 2.1.

$$P(X_{n+1} = j | X_n = i) = p_{ij}$$

Definition 2.1 (Markov chain). A (discrete time, discrete space, time homogeneous) Markov chain is specified by three ingredients:

- A state space S , any non-empty finite or countable set.
- Initial probabilities $\{v_i\}_{i \in S}$, where v_i is the probability of starting at i (at time 0). (So $v_i \geq 0$ and $\sum_i v_i = 1$)
- Transition probabilities $\{p_{ij}\}_{i,j \in S}$, where p_{ij} is the probability of jumping to j if you start at i . (So $p_{ij} \geq 0$, and $\sum_j p_{ij} = 1$ for all i)

Remark 2.1 (Markov property).

$$P(X_{n+1} = j | X_0 = i_0, X_1 = i_1, X_2 = i_2, \dots, X_n = i_n) = P(X_{n+1} = j | X_n = i_n) = p_{i_n j}$$

i.e. The probabilities at time $n + 1$ depend only on the state at time n .

Remark 2.2.

$$P(X_0 = i_0, X_1 = i_1, \dots, X_n = i_n) = v_{i_0} p_{i_0 i_1} p_{i_1 i_2} \dots p_{i_{n-1} i_n}$$

2.1 Markov Chain examples

Example 2.1 (the Frog Walk). Let $X_n :=$ pad index the frog is at after n steps.

$$\begin{aligned} S &= \{1, 2, 3, \dots, 20\} \\ v_{20} &= 1, v_i = 0 \forall i \neq 20 \\ p_{ij} &= \begin{cases} \frac{1}{3}, & |j - i| \leq 1 \text{ or } |j - i| = 19 \\ 0, & \text{otherwise} \end{cases} \end{aligned}$$

Example 2.2 (Bernoulli process).

$$\begin{aligned} S &= \{1, 2, 3, \dots\} \\ v_0 &= 1, v_i = 0 \forall i \neq 0 \\ p_{ij} &= \begin{cases} p, & j = i + 1 \\ 1 - p, & j = i \\ 0, & \text{otherwise} \end{cases} \end{aligned}$$

where $0 < p < 1$.

Example 2.3 (Simple random walk (s.r.w.)). Let $X_n :=$ net gain (in dollars) after n bets

$$\begin{aligned} S &= \{0, 1, 2, 3, \dots\} \\ v_a &= 1, v_i = 0 \forall i \neq a \\ p_{ij} &= \begin{cases} p, & j = i + 1 \\ 1 - p, & j = i - 1 \\ 0, & \text{otherwise} \end{cases} \end{aligned}$$

where $0 < p < 1, a \in \mathbb{Z}$.

Special case: When $p = 1/2$, call it simple symmetric random walk.

Example 2.4 (Ehrenfest's Urn). Let $X_n :=$ # balls in Urn 1 at time n .

We have d balls in total, divided into two urns. At each time, we choose one of the d balls uniformly at random, and move it to the other urn.

$$\begin{aligned} S &= \{1, 2, 3, \dots, d\} \\ v_a &= 1, v_i = 0 \forall i \neq a \\ p_{ij} &= \begin{cases} (d-i)/d, & j = i + 1 \\ i/d, & j = i - 1 \\ 0, & \text{otherwise} \end{cases} \end{aligned}$$

2.2 Elementary Computations

Notation 2.2.

$$\mu_i^{(n)} := P(X_n = i)$$

Notation 2.3.

$$\begin{aligned} m &:= |S| && \text{(the number of elements in S, could be infinity)} \\ \mu^{(n)} &= (\mu_1^{(n)}, \mu_2^{(n)}, \mu_3^{(n)}, \dots) && (m \times 1) \\ v &= (v_1, v_2, v_3, \dots) && (m \times 1) \\ P &= (p_{ij}) = \begin{pmatrix} p_{11} & p_{12} & \dots & p_{1m} \\ p_{21} & p_{22} & \dots & \\ & \ddots & & \\ p_{m1} & \dots & & p_{mm} \end{pmatrix} && (m \times m \text{ matrix}) \end{aligned}$$

Fact 2.1.

$$\begin{aligned} \mu^{(1)} &= vP = \mu^{(0)}P \\ \mu^{(n)} &= vP^n = \mu^{(0)}P^n \end{aligned}$$

Notation 2.4.

$$p_{ij}^{(n)} := P(X_n = j, X_0 = i) = P(X_{m+n} = j | X_m = i) \quad (\text{for any } m \in \mathbb{N})$$

Fact 2.2.

$$\begin{aligned} \sum_{j \in S} p_{ij}^{(n)} &= 1 \\ p_{ij}^{(1)} &= p_{ij} \\ P^{(n)} &= P^n \end{aligned} \quad (\text{for all } n \in \mathbb{N})$$

Notation 2.5.

$$\begin{aligned} P^0 &:= I \\ P^{(0)} &:= I \\ p_{ij}^{(0)} &= \begin{cases} 1 & i = j \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

Theorem 2.1 (Chapman-Kolmogorov equations).

$$\begin{aligned} p_{ij}^{(m+n)} &= \sum_{k \in S} p_{ik}^{(m)} p_{kj}^{(n)} \\ P_{ij}^{(m+s+n)} &= \sum_{k \in S} \sum_{l \in S} p_{ik}^{(m)} p_{kl}^{(s)} p_{lj}^{(n)} \end{aligned}$$

Matrix form:

$$\begin{aligned} P^{(m+n)} &= P^{(m)} P^{(n)} \\ P^{(m+s+n)} &= P^{(m)} P^{(s)} P^{(n)} \end{aligned}$$

Theorem 2.2 (Chapman-Kolmogorov Inequality).

$$\begin{aligned} p_{ij}^{(m+n)} &\geq p_{ik}^{(m)} p_{kj}^{(n)} && (\text{for all } k \in S) \\ P_{ij}^{(m+s+n)} &\geq p_{ik}^{(m)} p_{kl}^{(s)} p_{lj}^{(n)} && (\text{for any } k, l \in S) \end{aligned}$$

2.3 Recurrence and Transience

Notation 2.6.

$$\begin{aligned} P_i(\dots) &\equiv P(\dots | X_0 = i) \\ E_i(\dots) &\equiv E(\dots | X_0 = i) \\ N(i) &= \#\{n \geq 1 : X_n = i\} \\ &(\text{total number of times that the chain hits } i, \text{ not counting time } 0) \end{aligned}$$

Definition 2.2 (**return probability**). Let f_{ij} be the return probability from i to j .

$$f_{ij} := P_i(X_n = j \text{ for some } n \geq 1) \equiv P_i(N(j) \geq 1)$$

Fact 2.3.

$$1 - f_{ij} = P_i(X_n \neq j \text{ for all } n \geq 1) \quad (1)$$

$$P_i(N(i) \geq k) = (f_{ii})^k \quad (2)$$

$$P_i(N(j) \geq k) = f_{ij}(f_{jj})^{k-1} \quad (3)$$

$$f_{ik} \geq f_{ij}f_{jk} \quad (4)$$

Fact 2.4. $f_{ij} > 0$ iff $\exists m \geq 1$ with $p_{ij}^{(m)} > 0$, i.e., there is some time m for which it is possible to get from i to j in m steps.

Definition 2.3 (**recurrent and transient states**). A state i of a Markov chain is recurrent if $f_{ii} = 1$. Otherwise, i is transient if $f_{ii} < 1$.

Proposition 2.1. If Z is a non-negative integer, then

$$E(Z) = \sum_{k=1}^{\infty} P(Z \geq k)$$

Theorem 2.3 (**Recurrent State Theorem**). As follows

- State i is recurrent $\iff P_i(N(i) = \infty) = 1 \iff \sum_{n=1}^{\infty} p_{ii}^{(n)} = \infty$
- State i is transient $\iff P_i(N(i) = \infty) = 0 \iff \sum_{n=1}^{\infty} p_{ii}^{(n)} < \infty$

Proof.

$$\begin{aligned} P_i(N(i) = \infty) &= \lim_{k \rightarrow \infty} P_i(N(i) \geq k) && \text{(by continuity of probabilities)} \\ &= \lim_{k \rightarrow \infty} (f_{ii})^k && (P_i(N(i) \geq k) = (f_{ii})^k) \\ &= \begin{cases} 1, & f_{ii} = 1 \\ 0, & f_{ii} < 1 \end{cases} \end{aligned}$$

■

Therefore,

$$\begin{aligned}
\sum_{n=1}^{\infty} p_{ii}^{(n)} &= \sum_{n=1}^{\infty} P_i(X_n = i) \\
&= \sum_{n=1}^{\infty} E_i(\mathbf{1}\{X_n = i\}) \\
&= E_i\left(\sum_{n=1}^{\infty} \mathbf{1}\{X_n = i\}\right) \\
&= E_i(N(i)) \\
&= \sum_{k=1}^{\infty} P_i(N(i) \geq k) && \text{(by proposition 1.1)} \\
&= \sum_{k=1}^{\infty} (f_{ii})^k \\
&= \begin{cases} \infty, & f_{ii} = 1 \\ \frac{f_{ii}}{1-f_{ii}} < \infty, & f_{ii} < 1 \end{cases}
\end{aligned}$$

Example 2.5 (simple random walk). If $p = 1/2$ then $\forall i, f_{ii} = 1$. If $p \neq 1/2$, then $\forall i, f_{ii} < 1$

Proof. Consider state 0. We need to check if $\sum_{n=1}^{\infty} p_{00}^{(n)} = \infty$.

If n is odd, then $p_{00}^{(n)} = 0$.

If n is even, $p_{00}^{(n)} = P(\frac{n}{2} \text{ heads and } \frac{n}{2} \text{ tails on first } n \text{ tosses})$.

This is a Binomial(n, p) distribution, so

$$\begin{aligned}
p_{00}^{(n)} &= \binom{n}{n/2} p^{n/2} (1-p)^{n/2} \\
&= \frac{n!}{[(n/2)!]^2} p^{n/2} (1-p)^{n/2} \\
&= \frac{(n/e)^n \sqrt{2\pi n}}{[(n/2e)^{n/2} \sqrt{2\pi n/2}]^2} p^{n/2} (1-p)^{n/2} && \text{(Stirling's approximation)} \\
&= [4p(1-p)]^{n/2} \sqrt{2/\pi n}
\end{aligned}$$

Case 1: If $p = 1/2$, then $4p(1-p) = 1$, so

$$\begin{aligned}
\sum_{n=1}^{\infty} p_{00}^{(n)} &= \sum_{n=2,4,6,\dots}^{\infty} \sqrt{2/\pi n} \\
&= \sqrt{2/\pi} \sum_{n=2,4,6,\dots}^{\infty} n^{-1/2} \\
&= \sqrt{2/\pi} \sum_{n=1}^{\infty} 2k^{-1/2} \\
&= \infty
\end{aligned}$$

Therefore, state 0 is recurrent.

Case 2: If $p \neq 1/2$, then $4p(1-p) < 1$, so

$$\begin{aligned}
 \sum_{n=1}^{\infty} p_{00}^{(n)} &= \sum_{n=2,4,6,\dots} [4p(1-p)]^{n/2} \sqrt{2/\pi n} \\
 &< \sum_{n=2,4,6,\dots} [4p(1-p)]^{n/2} && \text{(Geometric Series)} \\
 &= \frac{4p(1-p)}{1-4p(1-p)} \\
 &< \infty
 \end{aligned}$$

Therefore, the state 0 is transient.

The same exact calculation applies to any other state i . ■

Theorem 2.4 (f-Expansion).

$$f_{ij} = p_{ij} + \sum_{k \in S, k \neq j} p_{ik} f_{kj}$$

Proof.

$$\begin{aligned}
 f_{ij} &= P_i(\exists n \geq 1 : X_n = j) \\
 &= \sum_{k \in S} P_i(X_1 = k, \exists n \geq 1 : X_n = j) \\
 &= P_i(X_1 = j, \exists n \geq 1 : X_n = j) + \sum_{k \neq j} P_i(X_1 = k, \exists n \geq 1 : X_n = j) \\
 &= P_i(X_1 = j)P_i(\exists n \geq 1 : X_n = j | X_1 = j) + \sum_{k \neq j} P_i(X_1 = k)P_i(\exists n \geq 1 : X_n = j | X_1 = k) \\
 &= p_{ij}(1) + \sum_{k \neq j} p_{ik}(f_{kj})
 \end{aligned}$$
■

Remark 2.3. The f-Expansion shows that $f_{ij} \geq p_{ij}$.

Remark 2.4. It essentially follows from logical reasoning: from i , to get to j eventually, we have to either jump to j immediately (with probability p_{ij}), or jump to some other state k (with probability p_{ik}) and then get to j eventually (with probability p_{kj})

2.4 Communicating States and Irreducibility

Definition 2.4 (communicating states). State i communicates with state j , written $i \rightarrow j$, if $f_{ij} > 0$.

Remark 2.5. i.e. if it is possible to get from i to j .

Notation 2.7. Write $i \leftrightarrow j$ if both $i \rightarrow j$ and $j \rightarrow i$.

Definition 2.5 (irreducibility). A Markov chain is irreducible if $i \rightarrow j$ for all $i, j \in S$, i.e., if $f_{ij} > 0$ for all $i, j \in S$. Otherwise, the chain is reducible.

Lemma 2.1 (Sum Lemma). If $i \rightarrow k$, and $l \rightarrow j$, and $\sum_{n=1}^{\infty} p_{kl}^{(n)} = \infty$, then $\sum_{n=1}^{\infty} p_{ij}^{(n)} = \infty$

Proof. Since $i \rightarrow k$, and $l \rightarrow j$, there exists $m, r \geq 1$ s.t. $p_{ik}^{(m)} > 0$ and $p_{lj}^{(r)} > 0$.
By the Chapman-Kolmogorov inequality,

$$p_{ij}^{(m+s+r)} \geq p_{ij}^{(m)} p_{kl}^{(s)} p_{lj}^{(r)}$$

Hence

$$\begin{aligned} \sum_{n=1}^{\infty} p_{ij}^{(n)} &\geq \sum_{n=m+r+1}^{\infty} p_{ij}^{(n)} \\ &= \sum_{s=1}^{\infty} p_{ij}^{(m+s+r)} && (s = n - m - r) \\ &\geq \sum_{s=1}^{\infty} p_{ij}^{(m)} p_{kl}^{(s)} p_{lj}^{(r)} \\ &= \underbrace{p_{ij}^{(m)}}_{+} \underbrace{p_{lj}^{(r)}}_{+} \underbrace{\sum_{s=1}^{\infty} p_{kl}^{(s)}}_{=\infty} \\ &= \infty \end{aligned}$$

■

Corollary 2.1 (Sum Corollary). If $i \leftrightarrow k$, then i is recurrent iff k is recurrent.

Proof. Setting $j = i$ and $l = k$ in the Sum Lemma: If $i \leftrightarrow k$, then $\sum_{n=1}^{\infty} p_{ii}^{(n)} = \infty \iff \sum_{n=1}^{\infty} p_{kk}^{(n)} = \infty$. ■

Theorem 2.5 (Cases Theorem). For an irreducible Markov chain, either

- (a) $\sum_{n=1}^{\infty} p_{ij}^{(n)} = \infty$ for all $i, j \in S$, and all states are recurrent (recurrent Markov chain);
or
- (b) $\sum_{n=1}^{\infty} p_{ij}^{(n)} < \infty$ for all $i, j \in S$, and all states are transient (transient Markov chain).

Theorem 2.6 (Finite Space Theorem). An irreducible Markov chain on a finite state space always falls into case (a), i.e., $\sum_{n=1}^{\infty} p_{ij}^{(n)} = \infty$ for all $i, j \in S$, and all states are recurrent.

Proof. Choose any state $i \in S$. We have

$$\begin{aligned} \sum_{j \in S} \sum_{n=1}^{\infty} p_{ij}^{(n)} &= \sum_{n=1}^{\infty} \sum_{j \in S} p_{ij}^{(n)} && (\text{exchanging the sums}) \\ &= \sum_{n=1}^{\infty} 1 \\ &= \infty \end{aligned}$$

Then if S is finite, it follows that there must exist at least one $j \in S$ with $\sum_{n=1}^{\infty} p_{ij}^{(n)} = \infty$. So we must be in case (a). ■

Notation 2.8. For $i \neq j$, let H_{ij} be the event that the chain hits the state i before returning to j , i.e.,

$$H_{ij} = \{\exists n \in \mathbb{N} : X_n = i, \text{ but } X_m \neq j \text{ for } 1 \leq m \leq n-1\}$$

Lemma 2.2 (Hit Lemma). If $j \rightarrow i$ with $j \neq i$, then $P_j(H_{ij}) > 0$.

Proof. Since $j \rightarrow i$, there is some possible path from j to i . i.e., there is $m \in \mathbb{N}$ and x_0, x_1, \dots, x_m with $x_0 = j$ and $x_m = i$ and $p_{x_r x_{r+1}} > 0$ for all $0 \leq r \leq m-1$.

Let $S = \max\{r : x_r = j\}$ be the last time this path hits j .

Then x_S, x_{S+1}, \dots, x_m is a possible path which goes from j to i without first returning to j . Hence $P_j(H_{ij}) \geq P(x_0, x_1, \dots, x_m) = p_{x_S x_{S+1}} p_{x_{S+1} x_{S+2}} \cdots p_{x_{m-1} x_m} > 0$ ■

Remark 2.6. If it is possible to get from j to i at all, then it is possible to get from j to i without first returning to j .

Intuitively obvious: If there is some path from j to i , then the final part of the path (starting with the last time it visits i) is a possible path from j to i which does not return to j .

Lemma 2.3 (f-Lemma). If $j \rightarrow i$ and $f_{jj} = 1$, then $f_{ij} = 1$

Proof. If $i = j$ it is trivial, so assume $i \neq j$.

Since $j \rightarrow i$, we have $P_j(H_{ij}) > 0$ by the Hit Lemma.

But one way to never return to j is to first hit i and then from i never return to j :

$$P_j(\text{never return to } j) \geq P_j(H_{ij})P_i(\text{never return to } j)$$

Therefore

$$1 - f_{jj} \geq P_j(H_{ij})(1 - f_{ij})$$

Since $f_{jj} = 1$, then $\underbrace{P_j(H_{ij})}_{>0}(1 - f_{ij}) = 0$

Hence $f_{ij} = 1$. ■

Lemma 2.4 (Infinite Returns Lemma). For an **irreducible** Markov chain, if it is **recurrent**, then

$$P_i(N(j) = \infty) = 1$$

for all $i, j \in S$.

But if it is **transient**, then $P_i(N(j) = \infty) = 0$ for all $i, j \in S$.

Proof. Let $i, j \in S$. If the chain is recurrent, then $f_{ij} = f_{jj} = 1$ by the f-Lemma. Then

$$\begin{aligned} P_i(N(j) = \infty) &= \lim_{k \rightarrow \infty} P_i(N(j) \geq k) \\ &= \lim_{k \rightarrow \infty} f_{ij}(f_{jj})^{k-1} \\ &= \lim_{k \rightarrow \infty} (1)(1)^{k-1} \\ &= 1 \end{aligned}$$

If the chain is transient, then $f_{jj} < 1$, then

$$\begin{aligned} P_i(N(j) = \infty) &= \lim_{k \rightarrow \infty} P_i(N(j) \geq k) \\ &= \lim_{k \rightarrow \infty} f_{ij}(f_{jj})^{k-1} \\ &= \lim_{k \rightarrow \infty} (1)(f_{jj})^{k-1} \\ &= 0 \end{aligned}$$

■

Theorem 2.7 (Recurrence Equivalence Theorem). If a chain is **irreducible**, then the following are equivalent (and all correspond to case (a)):

1. There are $k, l \in S$ with $\sum_{n=1}^{\infty} p_{kl}^{(n)} = \infty$.
2. For all $i, j \in S$, we have $\sum_{n=1}^{\infty} p_{ij}^{(n)} = \infty$.
3. There is $k \in S$ with $f_{kk} = 1$, i.e. k is recurrent.
4. For all $j \in S$, we have $f_{jj} = 1$, i.e. all states are recurrent.
5. For all $i, j \in S$, we have $f_{ij} = 1$.
6. There are $k, l \in S$ with $P_k(N(l) = \infty) = 1$.
7. For all $i, j \in S$, we have $P_i(N(j) = \infty) = 1$.

Proof. Follow from results that we have already proven

- 1 \implies 2: Sum Lemma.
- 2 \implies 4: Recurrent State Theorem (with $i = j$).
- 4 \implies 5: f-Lemma.
- 5 \implies 3: immediate.
- 3 \implies 1: Recurrent State Theorem (with $l = k$).
- 4 \implies 7: Infinite Returns Lemma.

- 7 \implies 6: Immediate.
- 6 \implies 3: Recurrent State Theorem (with $l = k$).

■

Theorem 2.8 (**Transience Equivalence Theorem**). If a chain is **irreducible**, then the following are equivalent (and all correspond to case (b)):

1. There are $k, l \in S$ with $\sum_{n=1}^{\infty} p_{kl}^{(n)} < \infty$.
2. For all $i, j \in S$, we have $\sum_{n=1}^{\infty} p_{ij}^{(n)} < \infty$.
3. For all $k \in S$, we have $f_{kk} < 1$, i.e. k is transient.
4. There is $j \in S$ with $f_{jj} < 1$, i.e. some state is recurrent.
5. There are $i, j \in S$ with $f_{ij} < 1$.
6. For all $k, l \in S$, $P_k(N(l) = \infty) = 0$.
7. There are $i, j \in S$ with $P_i(N(j) = \infty) = 0$.

Remark 2.7 (closed subset note). Suppose a chain is reducible, but it has a closed subset $C \subseteq S$ (i.e. $p_{ij} = 0$ for $i \in C$ and $j \notin C$) on which it is irreducible (i.e. $i \rightarrow j$ for all $i, j \in C$). Then, the Recurrence Equivalence Theorem and other results about irreducible chains still apply to the chain when **restricted** to C .

Proposition 2.2. For simple random walk with $p > 1/2$, $f_{ij} = 1$ whenever $j > i$. (Similarly, if $p < 1/2$ and $j < i$, then $f_{ij} = 1$.)

Proof. Let $X_0 = 0$, and $Z_n = X_n - X_{n-1}$ for $n = 1, 2, \dots$, so that $X_n = \sum_{i=1}^n Z_i$. Since Z_n s iid with $P(Z_n = 1) = p$ and $P(Z_n = -1) = 1 - p$, then by Law of Large Numbers,

$$\lim_{n \rightarrow \infty} \frac{1}{n} (Z_1 + Z_2 + \dots + Z_n) \stackrel{p}{=} E(Z_1) = p(1) + (1-p)(-1) = 2p - 1 > 0$$

$$\begin{aligned} \implies \infty &= \lim_{n \rightarrow \infty} (Z_1 + Z_2 + \dots + Z_n) \\ &= \lim_{n \rightarrow \infty} X_n - X_0 \\ &= \lim_{n \rightarrow \infty} X_n \end{aligned}$$

But if $i < j$, then to go from i to ∞ , the chain must pass through j , so $f_{ij} = 1$. ■

3 Markov Chain Convergence

3.1 Stationary Distributions

Definition 3.1 (stationary distributions). If π is a probability distribution on S (i.e. $\pi_i \geq 0$ for all $i \in S$, and $\sum_{i \in S} \pi_i = 1$), then π is stationary for a Markov chain with transition probabilities (p_{ij}) if $\sum_{i \in S} \pi_i p_{ij} = \pi_j$ for all $j \in S$ (or $\pi P = \pi$, in matrix notation).

Remark 3.1. Intuitively, π being stationary means if the chain starts with probabilities $\{\pi_i\}$, then it will keep the same probabilities one time unit later.

Definition 3.2 (doubly stochastic). A Markov Chain is doubly stochastic if in addition to the usual condition that $\sum_{j \in S} p_{ij} = 1$ for all $i \in S$, $\sum_{i \in S} p_{ij} = 1$ for all $j \in S$.

Remark 3.2. This holds for the Frog Example.

Proposition 3.1. If a Markov chain with states S satisfies $|S| < \infty$ and is doubly stochastic, then the uniform distribution on S is a stationary distribution.

Proof. Let $\{\pi_i\}$ be a distribution such that $\pi_i = \frac{1}{|S|}$.
Then

$$\begin{aligned} \sum_{i \in S} \pi_i p_{ij} &= \sum_{i \in S} \frac{1}{|S|} p_{ij} \\ &= \frac{1}{|S|} \sum_{i \in S} p_{ij} \\ &= \frac{1}{|S|} (1) && \text{(doubly stochastic)} \\ &= \frac{1}{|S|} \\ &= \pi_j \end{aligned}$$

Then $\{\pi_i\}$ is stationary. ■

3.2 Searching for Stationary

Definition 3.3 (reversibility). A Markov chain is reversible (or time reversible, or satisfies detailed balance) with respect to a probability distribution $\{\pi_i\}$ if $\pi_i p_{ij} = \pi_j p_{ji}$ for all $i, j \in S$.

Proposition 3.2. If a chain is reversible with respect to π , then π is a stationary distribution.

Proof. Reversibility means $\pi_i p_{ij} = \pi_j p_{ji}$, so then for $j \in S$,

$$\sum_{i \in S} \pi_i p_{ij} = \sum_{i \in S} \pi_j p_{ji} = \pi_j \sum_{i \in S} p_{ji} = \pi_j (1) = \pi_j$$

■

Lemma 3.1 (M-test). Let $\{x_{nk}\}_{n,k \in \mathbb{N}}$ be a collection of real numbers. Suppose that $\lim_{n \rightarrow \infty} x_{nk}$ exists for each fixed $k \in \mathbb{N}$. Suppose further that $\sum_{k=1}^{\infty} \sup_n |x_{nk}| < \infty$. Then $\lim_{n \rightarrow \infty} \sum_{k=1}^{\infty} x_{nk} = \sum_{k=1}^{\infty} \lim_{n \rightarrow \infty} x_{nk}$.

Proposition 3.3 (Vanishing Probabilities Proposition). If a Markov chain's transition probabilities satisfy that $\lim_{n \rightarrow \infty} p_{ij}^{(n)} = 0$ for all $i, j \in S$, then the chain does **not** have a stationary distribution.

Proof. Suppose for contradiction that there is a stationary distribution π . Then we would have $\pi_j = \sum_{i \in S} \pi_i p_{ij}^{(n)}$ for any n , so

$$\pi_j = \lim_{n \rightarrow \infty} \pi_j = \lim_{n \rightarrow \infty} \sum_{i \in S} \pi_i p_{ij}^{(n)}$$

$$\begin{aligned} \pi_j &= \lim_{n \rightarrow \infty} \pi_j \\ &= \lim_{n \rightarrow \infty} \sum_{i \in S} \pi_i p_{ij}^{(n)} \\ &= \sum_{i \in S} \lim_{n \rightarrow \infty} \pi_i p_{ij}^{(n)} \quad (\text{exchange the sum and the limit, which is valid by M-test}) \\ &= \sum_{i \in S} \pi_i \lim_{n \rightarrow \infty} p_{ij}^{(n)} \\ &= \sum_{i \in S} 0 \\ &= 0 \end{aligned}$$

So we would have $\pi_j = 0$ for all j . But this means that $\sum_j \pi_j = 0$, which is a contradiction. ■

Lemma 3.2 (Vanishing Lemma). If a Markov chain has some $k, l \in S$ with $\lim_{n \rightarrow \infty} p_{kl}^{(n)} = 0$, then for any $i, j \in S$ with $k \rightarrow i$ and $j \rightarrow l$, $\lim_{n \rightarrow \infty} p_{ij}^{(n)} = 0$.

Proof. Since $k \rightarrow i$ and $j \rightarrow l$, we can find $r, s \in \mathbb{N}$ with $p_{ki}^{(r)} > 0$ and $p_{jl}^{(s)} > 0$. Then by the Chapman-Kolmogorov Inequality,

$$p_{kl}^{(r+n+s)} \geq p_{ki}^{(r)} p_{ij}^{(n)} p_{jl}^{(s)}$$

Hence

$$p_{ij}^{(n)} \leq p_{kl}^{(r+n+s)} / p_{ki}^{(r)} p_{jl}^{(s)}$$

But the assumptions imply that

$$\lim_{n \rightarrow \infty} \left[p_{kl}^{(r+n+s)} / p_{ki}^{(r)} p_{jl}^{(s)} \right] = 0$$

Hence

$$\begin{aligned} 0 &\leq \lim_{n \rightarrow \infty} p_{ij}^{(n)} \leq 0 \\ \implies \lim_{n \rightarrow \infty} p_{ij}^{(n)} &= 0 \end{aligned}$$
■

Corollary 3.1 (Vanishing Together Corollary). For an **irreducible** Markov chain, either

1. $\lim_{n \rightarrow \infty} p_{ij}^{(n)} = 0$ for all $i, j \in S$, or
2. $\lim_{n \rightarrow \infty} p_{ij}^{(n)} \neq 0$ for all $i, j \in S$

Corollary 3.2 (Vanishing Probabilities Corollary). If an **irreducible** Markov chain's transition probabilities satisfy that $\lim_{n \rightarrow \infty} p_{kl}^{(n)} = 0$ for some $k, l \in S$, then the chain does not have a stationary distribution.

Lemma 3.3. If the x_n s are non-negative, and $\sum_{n=1}^{\infty} x_n < \infty$, then $\lim_{n \rightarrow \infty} x_n = 0$.

Corollary 3.3 (Transient Not Stationary Corollary). A Markov chain which is **irreducible and transient** cannot have a stationary distribution.

Proof. If a chain is irreducible and transient, then by the Transience Equivalence Theorem, $\sum_{n=1}^{\infty} p_{ij}^{(n)} < \infty$ for all $i, j \in S$. Hence $\lim_{n \rightarrow \infty} p_{ij}^{(n)} = 0$ for all $i, j \in S$. Thus by the Vanishing Probabilities Corollary, there is no stationary distribution. ■

3.3 Obstacles to Convergence

Definition 3.4 (period). The period of a state i is the greatest common divisor (gcd) of the set $\{n \geq 1 : p_{ii}^{(n)} > 0\}$, i.e. the largest number m such that all the values of n with $p_{ii}^{(n)} > 0$ are all integer multiples of m . If the period of each state is 1, we say the chain is aperiodic; otherwise we say the chain is periodic.

Remark 3.3. Intuitively, the period of a state i is the pattern of returning to i from i . e.g. If the period of i is 2, then it is only possible to get from i to i in an even numbers of steps.

Fact 3.1. If state i has period t , and $p_{ii}^{(m)} > 0$, then m is an integer multiple of t , i.e., t divides m .

Fact 3.2. If $p_{ii} > 0$, then the period of state i is 1.

Fact 3.3. If $p_{ii}^{(n)} > 0$ and $p_{ii}^{(n+1)} > 0$, then the period of state i is 1.

Lemma 3.4 (Equal Periods Lemma). If $i \leftrightarrow j$, then the periods of i and of j are equal.

Proof. Let the periods of i and j be t_i and t_j . Since $i \leftrightarrow j$, we can find $r, s \in \mathbb{N}$ with $p_{ij}^{(r)} > 0$ and $p_{ji}^{(s)} > 0$. Then

$$p_{ii}^{(r+s)} \geq p_{ij}^{(r)} p_{ji}^{(s)} > 0$$

Therefore by Fact 2.1, t_i divides $r + s$.

Suppose now that $p_{jj}^{(n)} > 0$. Then

$$p_{ii}^{(r+n+s)} \geq p_{ij}^{(r)} p_{jj}^{(n)} p_{ji}^{(s)} > 0$$

So t_i divides $r + n + s$.

Since t_i divides both $r + n + s$ and $r + s$, then it must divide n as well.

Since this is true for any n with $p_{jj}^{(n)} > 0$, it follows that t_i is a common divisor of $\{n \in \mathbb{N} : p_{jj}^{(n)} > 0\}$.

But t_j is the **greatest** such common divisor, so $t_j \geq t_i$.

Similarly we can show that $t_i \geq t_j$, so we have $t_i = t_j$. ■

Corollary 3.4 (Equal Periods Corollary). If a chain is **irreducible**, then all states have the same period.

Corollary 3.5. If a chain is **irreducible** and $p_{ii} > 0$ for some state i , then the chain is **aperiodic**.

3.4 Convergence Theorem

Theorem 3.1 (Markov Chain Convergence Theorem). If a Markov chain is **irreducible**, **aperiodic**, and has a stationary distribution $\{\pi_i\}$, then $\lim_{n \rightarrow \infty} p_{ij}^{(n)} = \pi_j$ for all $i, j \in S$, and $\lim_{n \rightarrow \infty} P(X_n = j) = \pi_j$ for any initial probabilities $\{v_i\}$.

Theorem 3.2 (Stationary Recurrence Theorem). If chain **irreducible** and has a stationary distribution, then it is **recurrent**.

Proof. The Transient Not Stationary Corollary says that a chain cannot be irreducible, transient and have a stationary distribution.

Therefore, if a chain is irreducible and has a stationary distribution, then it cannot be transient, i.e. it must be recurrent. ■

Lemma 3.5 (Number Theory Lemma). If a set A of positive integers is non-empty, and satisfies additivity, and $\gcd(A) = 1$, then there is some $n_0 \in \mathbb{N}$ s.t. for all $n \geq n_0$ we have $n \in A$ i.e. the set A includes all of the integers $n_0, n_0 + 1, n_0 + 2, \dots$

Proposition 3.4. If a state i has $f_{ii} > 0$ and is **aperiodic**, then there is $n_0(i) \in \mathbb{N}$ such that $p_{ii}^{(n)} > 0$ for all $n \geq n_0(i)$

Proof. Let $A = \{n \geq 1 : p_{ii}^{(n)} > 0\}$. Since $f_{ii} > 0$, then A is not empty.

If $m, n \in A$, then

$$p_{ii}^{(m+n)} \geq p_{ii}^{(m)} p_{ii}^{(n)} > 0$$

So $m + n \in A$, which shows that A satisfies additivity. Also $\gcd(A) = 1$ since the state i is aperiodic. Hence from the Number Theory Lemma, there is $n_0 \in \mathbb{N}$ such that for all $n \geq n_0$, we have $n \in A$ i.e. $p_{ii}^{(n)} > 0$. ■

Corollary 3.6. If a chain is **irreducible** and **aperiodic**, then for any states $i, j \in S$, there is $n_0(i, j) \in \mathbb{N}$ s.t. $p_{ij}^{(n)} > 0$ for all $n \geq n_0(i, j)$

Proof. Find $n_0(i)$ as in Proposition 2.3, and find $m \in \mathbb{N}$ with $p_{ij}^{(m)} > 0$.

Then let $n_0(i, j) = n_0(i) + m$

Then if $n \geq n_0(i, j)$, then $n - m \geq n_0(i)$, so $p_{ij}^{(n)} \geq p_{ii}^{(n-m)} p_{ij}^{(m)} > 0$. ■

Lemma 3.6 (Markov Forgetting Lemma). If a Markov chain is **irreducible and aperiodic**, and has stationary distribution $\{\pi_i\}$, then for all $i, j, k \in S$,

$$\lim_{n \rightarrow \infty} |p_{ik}^{(n)} - p_{jk}^{(n)}| = 0$$

Remark 3.4. Intuitively, after a long time n , the chain “forgets” whether it started from state i or from state j .

Proof. ■

long

Proof of Markov Chain Convergence Theorem ■

long

Corollary 3.7. If a chain is **irreducible**, then it has at most **one** stationary distribution.

Proof. By Markov Chain Convergence Theorem, any stationary distribution that it has must be equal to $\lim_{n \rightarrow \infty} P(X_n = j)$, so it is unique. ■

Definition 3.5 (convergence in distribution).

$$\forall a < b, \lim_{n \rightarrow \infty} P(a < X_n < b) = P(a < X < b)$$

Definition 3.6 (weak convergence).

$$\forall \epsilon > 0, \lim_{n \rightarrow \infty} P(|X_n - X| \geq \epsilon) = 0$$

Remark 3.5. This is “converge in probability”.

Definition 3.7 (strong convergence).

$$P(\lim_{n \rightarrow \infty} X_n = X) = 1$$

Remark 3.6. This is “converge almost surely”.

Remark 3.7. Strong convergence implies weak convergence, and weak convergence implies convergence in distribution.

Proposition 3.5. If $\{X_n\}$ is a simple symmetric random walk, then the absolute values $|X_n|$ converge weakly to positive infinity. ■

prove this

3.5 Periodic Convergence

Theorem 3.3 (Periodic Convergence Theorem). Suppose a Markov chain is **irreducible**, with **period** $b \geq 2$, and **stationary distribution** $\{\pi_i\}$. Then for all $i, j \in S$,

$$\lim_{n \rightarrow \infty} \frac{1}{b} [p_{ij}^{(n)} + \dots + p_{ij}^{(n+b-1)}] = \pi_j$$

and

$$\lim_{n \rightarrow \infty} \frac{1}{b} (P[X_n = j] + P[X_{n+1} = j] + \dots + P[X_{n+b-1} = j]) = \pi_j$$

and also

$$\lim_{n \rightarrow \infty} \frac{1}{b} P(X_n = j \text{ or } X_{n+1} = j \text{ or } \dots \text{ or } X_{n+b-1} = j) = \pi_j$$

Theorem 3.4 (Average Probability Convergence). If a Markov chain is **irreducible** with **stationary distribution** $\{\pi_i\}$ (whether periodic or not), then

$$\forall i, j \in S, \lim_{n \rightarrow \infty} \frac{1}{n} [p_{ij}^{(1)} + p_{ij}^{(2)} + \dots + p_{ij}^{(n)}] = \pi_j$$

i.e.,

$$\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{l=1}^n p_{ij}^{(l)} = \pi_j$$

prove this

Corollary 3.8 (Unique Stationary Corollary). If Markov chain P is **irreducible** (whether periodic or not), then it has at most **one** stationary distribution.

3.6 Application - MCMC Algorithms

section missing...

3.7 Application - Random Walks on Graphs

Let V be a non-empty finite or countable set. Let $w : V \times V \rightarrow [0, \infty)$ be a symmetric weight function so that $w(u, v) = w(v, u)$. (usual unweighted case: $w(u, v) = 1$ if there is an edge between u and v , otherwise $w(u, v) = 0$).

Let $d(u) = \sum_{v \in V} w(u, v)$ be the degree of the vertex u . Assume that $d(u) > 0$ for all $u \in V$ (for example, by giving any isolated point a self-edge).

Definition 3.8 ((simple) random walk on the (undirected) graph). Given a vertex set V with symmetric weights w , the (simple) random walk on the (undirected) graph (V, w) is the Markov chain with state space $S = V$ and transition probabilities $p_{uv} = \frac{w(u, v)}{d(u)}$ for all $u, v \in V$.

Remark 3.8. It follows that

$$\sum_{v \in V} p_{uv} = \frac{\sum_{v \in V} w(u, v)}{\sum_{v \in V} w(u, v)} = 1$$

Remark 3.9. The most common case is where each $w(u, v) = 0$ or 1 , so from u , the chain moves to one of the $d(u)$ vertices connected to u with equal probability.

Theorem 3.5 (Graph Stationary Distribution). Consider a random walk on a graph V with degrees $d(u)$. Assume that Z is **finite**. Then if $\pi_u = \frac{d(u)}{Z}$, then π is a stationary distribution for this walk.

Theorem 3.6 (Graph Convergence Theorem). For a random walk on a connected non-bipartite graph, if $Z < \infty$, then $\lim_{n \rightarrow \infty} p_{uv}^{(n)} = \frac{d(v)}{Z}$ for all $u, v \in V$, and $\lim_{n \rightarrow \infty} P[X_n = v] = \frac{d(v)}{Z}$ (for any initial probabilities). prove this

Theorem 3.7 (Graph Average Convergence). For a random walk on any connected graph with $Z < \infty$ (whether bipartite or not), for all $u, v \in V$,

$$\lim_{n \rightarrow \infty} \frac{1}{2} [p_{uv}^{(n)} + p_{uv}^{(n+1)}] = \frac{d(v)}{Z}$$

and

$$\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{l=1}^n p_{uv}^{(l)} = \frac{d(v)}{Z}$$

prove this

3.8 Application - Gambler's Ruin

Consider the following gambling game:

Let $0 < a < c$ be integers, and let $0 < p < 1$. Suppose player A starts with a dollars, player B starts with $c - a$ dollars, and they repeatedly bet. At each bet, A wins \$1 from B with probability p , or B wins \$1 from A with probability $1 - p$.

If X_n is the amount of money that A has at time n , then clearly $X_0 = a$, and $\{X_n\}$ follows a simple random walk.

Let $T_i = \inf\{n \geq 0 : X_n = i\}$ be the first time A has i dollars.

The Gambler's Ruin question What is $P_a(T_c < T_0)$, i.e., what is the probability that A reaches c dollars before losing all their money?

Answer: Define $s(a) := P_a(T_c < T_0)$, so that the probability we want to find is a function of the player's initial fortune a . Clearly $s(0) = 0$ and $s(c) = 1$.

For $1 \leq a \leq c - 1$, we have

$$\begin{aligned} s(a) &= P_a(T_c < T_0) \\ &= P_a(T_c < T_0, X_0 + 1) + P_a(T_c < T_0, X_1 = X_0 - 1) \\ &\quad \text{(A either wins or loses \$1 on the first bet)} \\ &= P(X_1 = X_0 + 1)P_a(T_c < T_0 | X_1 = X_0 + 1) + P(X_1 = X_0 - 1)P_a(T_c < T_0 | X_1 = X_0 - 1) \\ &= ps(a + 1) + (1 - p)s(a - 1) \end{aligned}$$

This gives $c - 1$ equations for the $c - 1$ unknowns, which can be solved by simple algebra:

$$\begin{aligned} ps(a) + (1 - p)s(a) &= ps(a + 1) + (1 - p)s(a - 1) && \text{(re-arranging)} \\ \implies s(a + 1) - s(a) &= \frac{1 - p}{p} [s(a) - s(a - 1)] \end{aligned}$$

Suppose $s(1) = x$ for some $x \in \mathbb{R}$, then

$$\begin{aligned}
s(1) - s(0) &= x \\
s(2) - s(1) &= \frac{1-p}{p}[s(1) - s(0)] = \frac{1-p}{p}x \\
s(3) - s(2) &= \frac{1-p}{p}[s(2) - s(1)] = \left(\frac{1-p}{p}\right)^2 x \\
\implies s(a+1) - s(a) &= \left(\frac{1-p}{p}\right)^a x && (\text{for } 1 \leq a \leq c) \\
\implies s(a) &= s(a) - s(0) \\
&= [s(a) - s(a-1)] + [s(a-1) - s(a-2)] + \dots + [s(1) - s(0)] \\
&= \left[\left(\frac{1-p}{p}\right)^{a-1} + \left(\frac{1-p}{p}\right)^{a-2} + \dots + \left(\frac{1-p}{p}\right) + 1 \right] x \\
&= \begin{cases} \left[\frac{\left(\frac{1-p}{p}\right)^a - 1}{\left(\frac{1-p}{p}\right) - 1} \right] x, & p \neq \frac{1}{2} \\ ax, & p = \frac{1}{2} \end{cases}
\end{aligned}$$

Since $s(c) = 1$, we can solve for x :

$$x = \begin{cases} \frac{\left(\frac{1-p}{p}\right)^c - 1}{\left(\frac{1-p}{p}\right) - 1}, & p \neq \frac{1}{2} \\ \frac{1}{c}, & p = \frac{1}{2} \end{cases}$$

We then obtain our final **Gambler's Ruin formula**:

$$s(a) = \begin{cases} \frac{\left(\frac{1-p}{p}\right)^a - 1}{\left(\frac{1-p}{p}\right)^c - 1}, & p \neq \frac{1}{2} \\ \frac{a}{c}, & p = \frac{1}{2} \end{cases}$$

Remark 3.10. We will sometimes write $s(a)$ as $s_{c,p}(a)$, to show the explicit dependence on c and p .

Example 3.1. $c = 10,000, a = 9,700, p = 0.5$, then

$$s(a) = a/c = 0.97$$

Example 3.2. $c = 10,000, a = 9,700, p = 0.49$, then

$$s(a) \approx \frac{1}{163,000}$$

Proposition 3.6 (). Let $T = \min(T_0, T_c)$ be the time when the Gambler's Ruin game ends. Then $P(T > mc) \leq (1 - p^c)^m$ where $m \in \mathbb{Z}^+$ and $P(T = \infty) = 0$, and $\mathbb{E}[T] < \infty$.

Proof. (1) If the player ever wins c bets in a row, then the game must be over. Then if $T > mc$, then the player has failed to win c bets in a row, despite having m independent attempts to do so.

But the probability of winning c bets in a row is p^c . So the probability of failing to win c bets in a row is $1 - p^c$. Therefore the probability of failing on m independent attempts is $(1 - p^c)^m$, as claimed.

(2) Then by continuity of probabilities,

$$P(T = \infty) = \lim_{m \rightarrow \infty} P(T > mc) \leq \lim_{m \rightarrow \infty} (1 - p^c)^m = 0$$

(3) We have

$$\begin{aligned} E(T) &= \sum_{i=1}^{\infty} P(T \geq i) \\ &\leq \sum_{i=0}^{\infty} P(T \geq i) \\ &= P(T \geq 0) + P(T \geq 1) + P(T \geq 2) + P(T \geq 3) + P(T \geq 4) + \dots \\ &\leq P(T \geq 0) + P(T \geq 0) + \dots + P(T \geq 0) + P(T \geq c) + P(T \geq c) + \dots \\ &= \sum_{j=0}^{\infty} cP(T \geq cj) \\ &\leq \sum_{j=0}^{\infty} c(1 - p^c)^j \\ &= \frac{c}{1 - (1 - p^c)} \\ &= \frac{c}{p^c} < \infty \end{aligned}$$

■

Remark 3.11. This says that, with probability 1 the Gambler's Ruin game must eventually end, and the time it takes to end has finite expected value.

3.9 Mean Recurrence Times

Definition 3.9 (mean recurrence time). The mean recurrence time of a state i is

$$m_i = E_i(\inf\{n \geq 1 : X_n = i\}) = E_i(\tau_i)$$

where $\tau_i = \inf\{n \geq 1 : X_n = i\}$

Remark 3.12. That is, m_i is the expected value of the time to return from i back to i .

Definition 3.10 (positive recurrence and null recurrence). A state is positive recurrent if $m_i < \infty$. It is null recurrent if it is recurrent but $m_i = \infty$.

Theorem 3.8 (Recurrence Time Theorem). For an irreducible Markov chain, either

1. $m_i < \infty$ for all $i \in S$, and there is a **unique** stationary distribution given by $\pi_i = 1/m_i$;
or

2. $m_i = \infty$ for all $i \in S$, and there is **no** stationary distribution.

Proposition 3.7. An irreducible Markov chain on a **finite** state space S always falls into case (i) above:

$m_i < \infty$ for all $i \in S$, and there is a **unique** stationary distribution given by $\pi_i = 1/m_i$.

Remark 3.13. The converse is false: There could be an example that has infinite state space $S = \mathbb{N}$, but still has a stationary distribution, so it falls into case (i).

3.10 Application - Sequence Waiting Times

Problem Suppose we repeatedly flip a fair coin and get Heads(H) or Tails(T) independently each time with probability $1/2$ each. Let τ be the first time the sequence HTH is completed. What is $E[\tau]$?

To find $E[\tau]$, we can use Markov chains.

Let X_n be the partial amount of the desired sequence (HTH) that the chain has “achieved so far” after n flips. Then we always have $X_\tau = 3$, since we “win” upon reaching state 3. Assume we “start over” right after we win ($X_{\tau+1} = 1$ if flip $(\tau + 1)$ is Heads, otherwise $X_{\tau+1} = 0$). Also, we take $X_0 = 0$, i.e., at the beginning we have not achieved any of the sequence.

Here, $\{X_n\}$ is a Markov chain with state space $S = \{0, 1, 2, 3\}$ and $P = \begin{pmatrix} 1/2 & 1/2 & 0 & 0 \\ 0 & 1/2 & 1/2 & 0 \\ 1/2 & 0 & 0 & 1/2 \\ 1/2 & 1/2 & 0 & 0 \end{pmatrix}$.

The mean waiting time of HTH is thus equal to the mean recurrence time of state 3.

Using the equation $\pi P = \pi$, it can be computed that the stationary distribution is $(0.3, 0.4, 0.2, 0.1)$. Therefore, by the Recurrence Time Theorem, the mean time to return from state 3 to state 3 (has the same probability as going from state 0 to state 3) is $1/\pi_3 = 10$.

4 Martingales

Roughly speaking, martingales are stochastic processes which “stays the same on average”.

4.1 Martingale Definitions

For a formal definition, let $\{X_n\}_{n=0}^\infty$ be a sequence of random variables. We assume throughout that random variables X_n have **finite expectation** (or are **integrable**): $E|X_n| < \infty \quad \forall n$.

Definition 4.1 (Martingale). A sequence $\{X_n\}_{n=0}^\infty$ is a martingale if for all n ,

$$E(X_{n+1} | X_0, \dots, X_n) = X_n$$

Remark 4.1. No matter what has happened so far, the average of the next value will be equal to the most recent one.

Special case: Markov chain If the sequence $\{X_n\}$ is a Markov chain, then we have

$$\begin{aligned} E[X_{n+1}|X_0 = i_0, \dots, X_n = i_n] &= \sum_{j \in S} j P[X_{n+1} = j | X_0 = i_0, \dots, X_n = i_n] \\ &= \sum_j j P[X_{n+1} = j | X_n = i_n] \\ &= \sum_j j p_{i_n, j} \end{aligned}$$

To be a martingale, this value must equal i_n . That is, a Markov chain (with $E|X_n| < \infty$) is a martingale if

$$\sum_{j \in S} j p_{ij} = i$$

for all $i \in S$.

Example 4.1 (simple symmetric random walk). Let $\{X_n\}$ be s.s.r.w. with $p = 1/2$. We always have $|X_n| \leq n$, so $E|X_n| \leq n < \infty$, so there is no problem with finite expectations. For all $i \in S$, we compute that $\sum_{j \in S} j p_{ij} = (i+1)(1/2) + (i-1)(1/2) = i$, so s.s.r.w. is indeed a martingale.

Proposition 4.1. If $\{X_n\}$ is a martingale, then by the Law of Total Expectation,

$$\begin{aligned} E(X_{n+1}) &= E[E(X_{n+1}|X_0, X_1, \dots, X_n)] = E(X_n) \\ \implies E(X_n) &= E(X_0) \quad \forall n \end{aligned}$$

This is not surprising, since martingales stay the same on average. However, this is not a sufficient condition for $\{X_n\}$ to be a martingale.

4.2 Stopping Times

We often want to consider $E(X_T)$ for a random time T . We need to prevent the random time T from looking into the future of the process, before deciding whether to stop.

Definition 4.2 (stopping time). A non-negative-integer-valued random variable T is a stopping time for $\{X_n\}$ if the event $\{T = n\}$ is determined by X_0, X_1, \dots, X_n , i.e. if the indicator function $\mathbf{1}\{T = n\}$ is a function of X_0, X_1, \dots, X_n .

Remark 4.2. Intuitively, this definition says that a stopping time T must decide whether to stop at time n based solely on what has happened up to time n , without first looking into the future.

Example 4.2. valid stopping times:

$T = 5, T = \inf\{n \geq 0 : X_n = 5\}, T = \inf\{n \geq 0 : X_n = 0 \vee X_n = c\}, T = \inf\{n \geq 2 : X_{n-2} = 5\}$ not valid stopping time: $T = \inf\{n \geq 0 : X_{n+1} = 5\}$ (since it looks into the future)

Lemma 4.1 (Optional Stopping Lemma). If $\{X_n\}$ is a martingale, and T is a stopping time which is **bounded** (i.e., $\exists M < \infty$ with $P(T \leq M) = 1$), then

$$E(X_T) = E(X_0)$$

Example 4.3. Consider s.s.r.w. with $X_0 = 0$, and let

$$T = \min\{10^{12}, \inf\{n \geq 0 : X_n = -5\}\}$$

Then T is a bounded stopping time. Hence by the Optional Stopping Lemma,

$$E(X_T) = E(X_0) = E(0) = 0$$

But near always, we will have $X_T = -5$.

By the Law of Total Expectation,

$$\begin{aligned} 0 &= E(X_T) \\ &= \underbrace{P(X_T = -5)}_{\approx 1} \underbrace{E(X_T | X_T = -5)}_{=-5} + \underbrace{P(X_T \neq -5)}_{\approx 0} \underbrace{E(X_T | X_T \neq -5)}_{\text{huge}} \end{aligned}$$

Theorem 4.1 (Optional Stopping Theorem). If $\{X_n\}$ is a martingale with stopping time T , and $P(T < \infty) = 1$, and $E|X_T| < \infty$, and $\lim_{n \rightarrow \infty} E(X_n \mathbb{1}\{T > n\}) = 0$, then

$$E(X_T) = E(X_0)$$

Proof. For each $m \in \mathbb{N}$, let $S_m = \min\{T, m\}$, so that S_m is a bounded stopping time.

Then by Optional Stopping Lemma, $E(X_{S_m}) = E(X_0)$ (for any m).

Then for any m ,

$$\begin{aligned} X_{S_m} &= X_{\min(T, m)} \\ &= X_T \mathbb{1}\{T \leq m\} + X_m \mathbb{1}\{T > m\} \\ &= X_T(1 - \mathbb{1}\{T > m\}) + X_m \mathbb{1}\{T > m\} \\ &= X_T - X_T \mathbb{1}\{T > m\} + X_m \mathbb{1}\{T > m\} \\ \implies X_T &= X_{S_m} + X_T \mathbb{1}\{T > m\} - X_m \mathbb{1}\{T > m\} \\ \implies E(X_T) &= E(X_{S_m}) + E(X_T \mathbb{1}\{T > m\}) - E(X_m \mathbb{1}\{T > m\}) \\ &= E(X_0) + E(X_T \mathbb{1}\{T > m\}) - E(X_m \mathbb{1}\{T > m\}) \end{aligned}$$

Take $m \rightarrow \infty$. Since $P(T < \infty) = 1$, we have $\mathbb{1}\{T > m\} \rightarrow 0$.

Since $E|X_T| < \infty$ and $\mathbb{1}\{T > m\} \rightarrow 0$, we have

$$\lim_{m \rightarrow \infty} E(X_T \mathbb{1}\{T > m\}) = 0$$

by the Dominated Convergence Theorem 1.1

Also, $\lim_{m \rightarrow \infty} E(X_m \mathbb{1}\{T > m\}) = 0$ by assumption.

Hence $E(X_T) \rightarrow E(X_0)$, i.e. $E(X_T) = E(X_0)$. ■

Corollary 4.1 (Optional Stopping Corollary). If $\{X_n\}$ is a martingale with stopping time T , which is “bounded up to time T ” (i.e., $\exists M < \infty$ with $P(|X_n| \mathbb{1}\{n \leq T\} \leq M) = 1$ for all n), and $P(T < \infty) = 1$, then

$$E(X_T) = E(X_0)$$

Proof. It follows that, $P(|X_T| \leq M) = 1$.

Hence, $E|X_T| \leq M < \infty$.

Also,

$$\begin{aligned}
 |E(X_n \mathbf{1}\{T > n\})| &\leq E(|X_n| \mathbf{1}\{T > n\}) \\
 &= E(|X_n| \mathbf{1}\{n \leq T\} \mathbf{1}\{T > n\}) \\
 &\leq E(M \mathbf{1}\{T > n\}) \\
 &= MP(T > n) \rightarrow 0 \qquad \qquad \qquad (\text{Since } P(T < \infty) = 1)
 \end{aligned}$$

Hence the result follows from the Optional Stopping Theorem. ■

Example 4.4 (Gambler's Ruin problem - $p = 1/2$). Let $T = \inf\{n \geq 0 : X_n \vee X_n = c\}$ be the time when the game ends. Then $P(T < \infty) = 1$ by Proposition 3.6. Also, if the game has not yet ended, i.e. $n \leq T$, then X_n must be between 0 and c . Hence $|X_n| \mathbf{1}\{n \leq T\} \leq c < \infty$ for all $n \leq T$.

So by the Optional Stopping Corollary 4.1, $E(X_T) = cs(a) + 0(1 - s(a)) = E(X_0) = a \implies s(a) = a/c$.

Example 4.5 (Gambler's Ruin problem - $p \neq 1/2$).